An AIAA, AIA, and NAFEMS Implementation Paper

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DIGITAL THREAD:
DEFINITION, VALUE, AND REFERENCE MODEL

AUTHORED BY THE
AIAA Digital Engineering
Integration Committee

APPROVED BY THE
AIAA Public Policy Committee

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Technical Operations Council in January 2023

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Statement of Attribution

This paper was drafted over the summer and fall of 2021, extensively revised and edited throughout 2022 based on feedback from multiple review panels, approved by the AIAA Public Policy Committee, the Aerospace Industries Association (AIA) Technical Operations Council, the Americas Regional Steering Committee of the International Association for the Engineering Modelling, Analysis and Simulation Community (NAFEMS) and the paper authors would like to acknowledge the support from the International Council on Systems Engineering (INCOSE) MBSE Patterns Working Group as a substantial contributor to this paper and partner in realizing its recommended outcomes.

The paper is the result of a joint effort from several 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 Thread as presented in this paper.

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AIAA Digital Thread Position Paper

Executive Summary & Purpose

This paper is one in a series of papers published by the AIAA Digital Engineering Integration Committee (DEIC). Although the concept of the Digital Thread has been discussed and specific aspects of the Digital Thread are not new, this paper attempts to consolidate in one location a description representing the DEIC's position on Digital Thread. The Digital Thread is central to the aerospace industry's digital transformation. Put simply, the Digital Thread can be defined as

> *A linked set of digital artifacts whose consistency is actively managed over the life cycle of a product, process, or system.*

The confluence of technologies and disciplines such as physics-based engineering modeling and simulation, artificial intelligence, big data, elastic cloud storage, and the internet of things (IoT) advance digital transformation in many sectors of the economy; however, their application is not sufficient for the digital transformation of the aerospace industry. In this context, digital transformation must impact decision making, and this is where the Digital Thread is foundational.

The complexity of aerospace systems necessitates a mixture of modeling approaches, from conceptual system models to detailed three-dimensional models. The diversity and evolutionary nature of the models, data sets, practices, and regulatory requirements of this industry pose significant challenges and emphasize the importance of managing consistency across the life cycle. The models are contained in intricate technology stacks consisting of commercial-off-the-shelf (COTS), government-off-the-shelf (GOTS), free open-source software (FOSS), and custom-developed tools and simulations, including proprietary tools and simulations that complicate and restrict model sharing. If not properly managed and aggregated, the vast amounts of data (measured and simulated) lead to missed opportunities to leverage collective knowledge and reuse of information [1]. Even subtle inconsistencies in a nonlinear and mission-critical system can be significant and lead to latent and costly defects over generational life cycles. Managing consistency of these models within each technology and cultural stack is problematic, and the ability to interact between these stacks when different organizations need to collaborate is daunting. The Digital Thread, when mechanized in a digital ecosystem, becomes the authorized environment for managing the consistency of this information across technology and cultural stacks. This makes the quantification and propagation of uncertainty regarding the evolving information within the Digital Thread all the more important to support timely, well-informed decision making throughout the product life cycle. Finally, by enabling the connection between the physical and virtual, the Digital Thread is foundational to developing and implementing valid Digital Twins1 [2, 3].

Members from academia, industry, and government collaborated on this paper with these objectives:

1. Provide the aerospace community with a standard definition of the Digital Thread
2. Discuss the value proposition for the creation and use of the Digital Thread as it relates to model-based engineering and enabling data analytics on the product life cycle
3. Describe a generic architecture framework for the Digital Thread
4. Provide recommendations for future focus areas and activities to accelerate value realization using the Digital Thread

This paper provides a detailed Digital Thread definition, value statement, and reference model, and recommends five actions associated with the business case, technical considerations, and education and training. Furthermore, this paper also recommends the establishment of a body to orchestrate collaboration between academia, industry, government, and relevant certification authorities to tackle the business, technical standards, cultural needs, gaps, and challenges identified by the authors.

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1. A Digital Twin is a virtual representation of a connected physical asset. A more detailed definition can be found in the Glossary of this paper.

Details and issues related to the implementation of the Digital Thread will be the topic of a follow-on paper.

Definition

What is the Digital Thread?

Building on the short definition in the previous section, The Digital Thread is a collection of linked authoritative2 digital information pertaining to a process, product, or system, whose consistency is actively managed throughout the life cycle. This enables accessibility, traceability, currency, applicability, and credibility of information, thus facilitating the capture, communication, and use and reuse of knowledge to efficiently inform decisions that realize value.

The Digital Thread is an engineered digital system. It describes the comprehensive linkage of models and related product information, encompasses the entire product life cycle, and includes customers, suppliers, partners, and configuration management. The system of interest (SOI) can be a product or service and can be as broad as the definition of a system [4]. For example, consider the Digital Thread for a research and development system that produces technologies. The Digital Thread seamlessly connects information across an SOI's life cycle to enable in-depth understanding, tracking, and reusability of the knowledge acquired during its life [5]. Seamless digital linkage means the data and information on the Digital Thread are produced and consumed within digital, scalable, and flexible frameworks without manual handoffs, as suggested by Figure 1.

Types of Information

The information linked within the Digital Thread consists of all the data and models used to describe all aspects of the system throughout its life cycle [6, 7]. This information can take many forms, from descriptive to computational models and data. The Digital Thread captures and links together many other elements, including collections of metadata, product development planning/backlogs, documentation, cost, sourcing information, etc. The Digital Thread also links to alternative system concepts. As concepts mature iteratively, information must remain synchronized and consistent across the many relationships. Additionally, new relationships between data may arise in subsequent iterations, and some relationships may no longer be needed. The Digital Thread must account for, and efficiently facilitate, the highly iterative nature of product development, product support, institutional learning, and effective decision making over time. The Digital Thread supports frequent (even continuous) integration and testing of these concepts at each iteration, enabling "real-time and long-term decision making" [5].

Model-Based Engineering and the Digital Thread

Model-based engineering (MBE) is defined by the National Institute of Standards and Technology (NIST) as "an approach to product development, manufacturing and life cycle support that uses a digital model to drive all engineering activities" [8]. Using MBE methodologies enables the capture and expression of analyzable representations of a system of interest. Because models developed within the

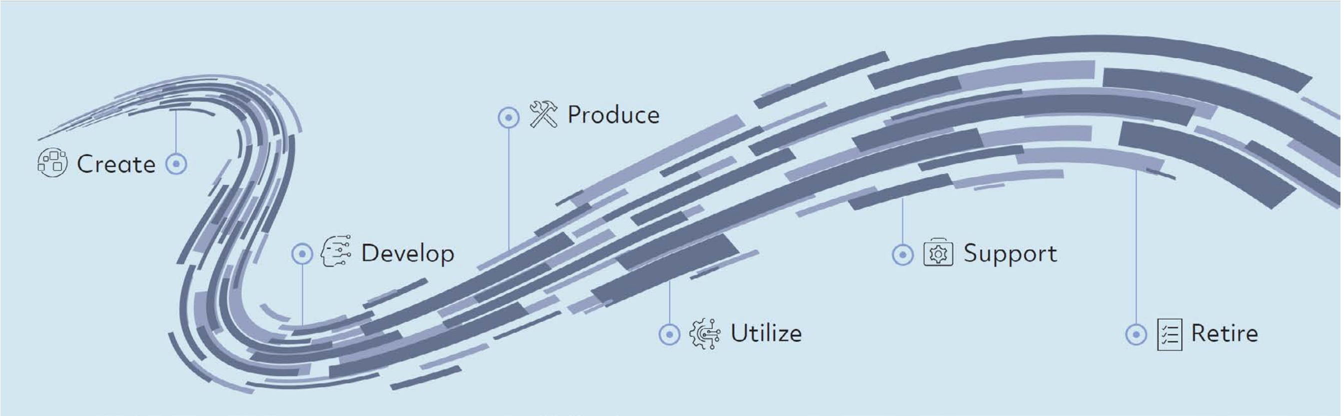

Figure 1. The Digital Thread.

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2. Three sources (stakeholders, experience, and observations) of authority are defined and discussed in Section 4 (see Figure 9).

Digital Thread have context, traceability, provenance, relationships to other models, and increased value, the Digital Thread supports and enhances the MBE approach. NIST further describes a core tenet of MBE: "data is created once and reused by all downstream data consumers" [8] — there is an authoritative instance of each datum within an MBE environment. The Digital Thread encompasses the identification, capture, management, dissemination, and assurance of authoritative sources for relevant product and life cycle data; in an MBE environment, a digital ecosystem uses the Digital Thread to manage and provide authoritative data in model form. The ability to connect tools and processes used in the MBE environment allows the digital models to become authoritative sources of truth.

A model may consist of data, states, behaviors, and relationships to other models. Some models, like the model of a requirement, are descriptive; others, such as a finite element model, are computational. The Digital Thread provides a structure to store model data and states, links models to each other (relationships), and manages the execution environment for model behaviors (as software). The integration capabilities of the Digital Thread can then be leveraged to automate cross-model analysis or reporting, such as traceability reports for life cycle data (requirements – design – test) or the buildup of technical measures like mass or power. Similarly, Digital Threads can chain models together to enable system analyses at multiple scales, multiple fidelities, or across disciplines. For example, a Digital Thread could partially or fully automate the analysis of aeroelastic effects by integrating a model-based definition of the aircraft, mesh generation software, computational fluid dynamics software, and finite element software.

The Digital Thread provides the foundational capabilities to create, maintain and disseminate the digital models at the heart of MBE. It also provides a base for developing advanced capabilities like multidisciplinary analysis or for developing automated or assistive capabilities that can reduce the workload of engineers or operators.

The Digital Thread has many characteristics; four examples are described below:

- A reference, i.e., a simple pointer indicating relationship or dependency; there should be no isolated entities in a Digital Thread
- A continuous connection between entities (e.g., part of an automated workflow), preferably with no "air gaps"3 or parts of the thread that exist in paper or human memory only
- The above associative connections between entities need to be kept consistent or at least identified for inconsistencies
- Subject to validation that confers status as an Authoritative Source of Truth (Asset) on the entity

Linked information is used in many ways, for instance, to trace 1) the evidence and rationale that led to a decision or 2) the provenance of data or requirements — and their maturation through the life cycle. A forthcoming Implementation paper in the AIAA series will address specific semantic implementations of the Digital Thread.

Classic systems engineering methodologies strive to mitigate inconsistencies; however, the increased interrelated nature of our complex aerospace systems makes it extremely difficult to minimize or eliminate inconsistencies. In the past, the linked relationships that resemble the Digital Thread were captured in various documents (at best). For example, product development standards, such as AS9145 [9], facilitated the capture of these linked relations that could be called an "engineering thread." Without the Digital Thread, the referenced links were static, often tacit, and easily broken or lost. Links were references and cross-references, and revisions of documents. These documents could contain input and output of the models and even a sufficiently detailed model description that could be used for reconstruction.

The Digital Thread, comprising linked relationships, enables decision management over time, which accelerates engineering solutions throughout the entire life cycle. The Digital Thread also includes a myriad of alternative concepts and decisions not pursued during the product life cycle. In this way,

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3. Isolated systems where "air gaps" are imposed for legal, privacy, or security reasons including systems with personal health care, export controlled, or classified information are in tension with the ideal aim of digital continuity. Additionally, temporary disconnects from field data or data across organizational boundaries may be needed. Nevertheless, in these situations, digital continuity may be approximated by virtual, proxy, or buffered connections.

useful alternative concepts, including design rationale, can be developed to meet other needs and form new Digital Threads for those concepts. The Digital Thread provides the lowest level of information linkage between digital representations through all length scales and stages of a product's life cycle. The Digital Thread must expose and manage inconsistencies while accelerating product development, production, and operations. Likewise, the Digital Thread provides information linkage across organizations and captures valuable institutional knowledge. Given this expansive definition, one might ask, what the Digital Thread is not?

A Digital Thread covers a life cycle segment of interest to the enterprise—perhaps the entire life cycle but possibly less, if justifiable. The key point is that the Digital Thread is more than a single artifact or collection of disconnected artifacts; it is a connected set of artifacts showing traceable relationships. The Digital Thread is more than a model or collection of models that represent the system of interest. In other words, the Digital Thread is more than a SysML model or an executable representation of the system. By making accessible authoritative sources of truth, the Digital Thread itself ought to become an authoritative source of truth. By integrating models with sources of data and its provenance (captured using metadata), the Digital Thread enables digital continuity over time and across domains, and, as such, is not to be confused with a collection of discrete, siloed digital artifacts. Similarly, the Digital Thread is not solely a collection of links. The Digital Thread facilitates the connection between the physical and virtual and is the foundation for developing and implementing valid Digital Twins. The details pertaining to the implementation of the Digital Thread will be discussed in a forthcoming Implementation paper in the AIAA series.

Value

A Digital Thread needs to be engineered and constructed to bring value to the organization(s) that develop, support, and maintain it. Traditionally, value is often associated with return on investment (ROI); however, herein a more expansive viewpoint is taken. At its core, the Digital Thread is one of the foundational technologies for accelerating and facilitating the agile capture, maintenance, and use of models, simulation data, experimental/operational data, and associated metadata throughout the lifecycle. Fujimoto describes three degrees of integration relevant to the Digital Thread: integrateability, interoperability, and composability [10]. Integrateability encompasses the information technology connectivity of data and models. Interoperability enables the collaborative execution of models. Composability provides combinatorial assembly and execution of simulations from component models. The Digital Thread can similarly be viewed as an implementation of FAIR principles (findability, accessibility, interoperability, and reusability) in an engineering context [11]. Integrateability corresponds to findability and accessibility, and composability relates to reusability. Interoperability has a similar meaning in both conceptions. The integration qualities of the Digital Thread enable both the development of multi-fidelity, multi-scale, and multidisciplinary analysis capabilities and the construction of digital system models or Digital Twins to support system qualification, operations, and maintenance.

The interrelated qualities of the Digital Thread extend beyond those mentioned above to include:

Bidirectional traceability: The ability to link, trace, reconcile, and communicate configuration managed data and models across the product life cycle at scale (from nano to global) is crucial for highly complex, safety-critical, and mission-critical aerospace products/systems. Singh and Willcox describe the Digital Thread as linkages of primary or authoritative information generated from all product life cycle phases [5]. The linkages facilitate bidirectional traceability or navigability of product information in the thread. Thus, one can follow the relationships in the Digital Thread to traverse either along or across the system's life cycle. This helps ensure that the right product is being developed and increases our understanding of how uncertainty propagates throughout the product life cycle. Finally, linking operational data back to the design phase helps inform and improve current and subsequent generations of products.

Consistency: Identifying and preserving the authoritative information and attributing the relationships between authoritative data and models produce the quality of consistency as described in the Generic Reference Model section. A Digital Thread assures that all stakeholders work with a set of self-consistent authoritative data, i.e., all authoritative derivative (or successor) information is fully compatible with its authoritative parent (or predecessor) information. The orchestration of version control systems is also key to manage change in models and documents, track the changes that were made and by whom, revert to previous versions when needed, and ensure that teams work from the same version of tools, models, and documents. Likewise, the Digital Thread can trace the impact of a change in any one information item to upstream and downstream items, accurately identifying inconsistency within a product's body of information until all impacted information items are updated. Incorporating configuration management into the Digital Thread enables stakeholders to work with different, self-consistent baselines. Thus, operations can work with a consistent baseline describing as-built systems in operation, while the development team works with a derivative and consistent baseline to design system upgrades. When extended across the supply chain, the Digital Thread makes it possible to digitally identify, track, and verify parts and products [12]. By capturing product design information, process capabilities, and product quality and integrity, the Digital Thread helps ensure that parts meet their desired specifications and that all relevant protocols are followed [12, 13]. The Digital Thread enables the ability to provide security and cybersecurity controls to enforce data rights to supplier data, ensure that only an authorized person sees appropriate data, and that the authoritative source of data was not corrupted. This digital encapsulation can be further extended to the distribution and use of the product of interest to help support inventory management and after-sales operations [14].

Increased communication and collaboration across teams, stakeholders, and customers: Together, the consistency and integration qualities of the Digital Thread tackle major risks (e.g., integration difficulties) to projects developing complex systems. For instance, missing data and poor communication could be major contributors to those risks, leading to engineering problems [15]. Knowledge workers on projects can spend 30% of their time searching for information, and it typically takes up to eight attempts to find an accurate search result [16, 17]. More specifically, engineers spend large amounts of time searching, integrating, and providing data [18]. For example, information integration and dissemination tend to be the dominant activity in the months leading to major life cycle reviews like preliminary design reviews. Furthermore, when teams work with old or incorrect information, product defects result; defects can also result from discovering new knowledge during development that is not properly disseminated to all affected parties. The Digital Thread qualities of consistency and integration reduce 1) the incidents of poor communication and 2) the workload of integrating product and life cycle information across disciplines and teams. In addition, the preservation and linking of all relevant metadata enable the documentation of decision processes and outcomes, allowing teams to capture the steps that lead to a decision and make available the assumptions formulated throughout the design process in a transparent manner. Such capability also facilitates the integration of latecomers or stakeholders that may contribute at different levels of the analysis [19, 20].

Workflow automation: Consistency and integration are also foundational for workflow automation within the Digital Thread; relationships among information items virtualize the chain of inputs and outputs within engineering workflows. The integration capabilities of the Digital Thread enable the connectivity of preprocessing, analysis, and postprocessing software in engineering workflows. Combined, teams can partly or fully automate:

- The retrieval of authoritative information
- The translation, transformation, and fusion of that information for input into an analysis activity
- The collaborative execution of models and software tools that produce raw analysis data
- The postprocessing that visualizes or reduces the analysis data for consumption by analysts or downstream activities

Hence, one could envision that even a semiautomated Digital Thread could automatically execute parts of engineering workflows in response to a change. For example, an approved change to a computer-aided design (CAD) model of an aircraft that changes the aircraft's geometry could automatically execute a computational fluid dynamics (CFD) workflow to update the aircraft's aerodynamics model. In circumstances for which workflow automation is not desirable, engineering judgement and control over analysis workflow can be informed by means of dashboards and notification systems and facilitated by the integration capabilities of the Digital Thread.

Analytical capabilities: By enabling information connectivity and continuity, the Digital Thread provides the foundational basis to many analytical capabilities critical to the ability to identify and quantify risks and uncertainties, and make informed decisions over the entire life cycle [21]. For example, by maintaining the complex relationships between part geometry and manufacturing processes, as well as physical and virtual testing, the Digital Thread helps identify and quantify the impact that specific inputs have on an outcome of interest (quality, reliability, manufacturability, etc.) and establish correlations among parameters that are not easily identifiable or quantifiable through physical experiments [1]. In a broader sense, when supported by a robust analytics infrastructure (compute, storage, algorithms, etc.), the Digital Thread facilitates:

- **Descriptive analytics:** Linking together requirements and functional models with results from detailed disciplinary analyses to rapidly evaluate the current state of a system against the requirements to be satisfied [21].
- **Predictive analytics:** When calibrated and updated with data representing the system's current state, models can more accurately predict future states of the system and quantify margins and uncertainties for quantities of interest [21].
- **Prescriptive analytics:** Recommending a course of actions based on a specific (predictive) outcome.

Knowledge and model reuse: The Digital Thread, through semantic ontologies, knowledge graphs [22], and federation [23], enables the indexing, archiving, integration, and retrieval of life cycle data representations and models. This, in turn, allows for the exploration, sharing and reuse of data, domain knowledge, and models [24] in the development of both current and new design configurations [25]. By representing domain semantics, ontologies provide a means to standardize data representations, which is essential to the qualities of interoperability and integration of the Digital Thread.

By making available metadata associated with model artifacts and synchronizing validation data with their respective models, the Digital Thread provides designers and decision makers with critical information regarding the purpose, scope, and degree of accuracy of existing models as well as the models' assumptions and domains of validation and application. Such traceability promotes appropriate model and design reuse [26, 27].

Generic Reference Model

With the above values in mind, a shared understanding of the problem definition space is necessary. Since individual enterprises and supply chain situations vary, such a shared understanding needs to be described in a sufficiently general way to cover this range, but with sufficient precision and parameterization to allow configuration of the related concepts to individual implementations. Accordingly, this section provides a generic reference model.

Defining the meaning of Digital Thread in a single sentence or short paragraph has real value but is less complete than such a reference model. The reference model discussed herein complements the prose definition and previous discussion by providing an actual configurable system model that is neutral (descriptive, not prescriptive) and can be used for planning, describing, and analyzing ecosystems using or planning Digital Thread capabilities. This generic reference model describes a uniform set of concepts that all Digital Threads or their surrounding related context have in common—although to varying degrees and through varied implementations. Concrete examples of Digital Threads are of great interest, but having a common underlying conceptual framework allows for the understanding of key issues and individual examples through a unifying lens.

Even in a single enterprise and program, the range of applications of a Digital Thread can be very large. The reference model contemplates possible applications across the full engineered product life cycle such as described by ISO 15288. Early product stakeholder needs analysis, defining and validating product technical requirements, defining the product architecture and its detailed design, verification of that design by analysis, simulation and test, and manufacturing engineering, as well as production operations, operational service, product sustainment, and retirement. All provide environments for Digital Thread information application use cases. This breadth can seem bewildering, so a key contribution of the reference model on consistency management is described below, using a paradigm that encompasses this diversity into a single manageable perspective.

The generic reference model is a model of the Digital Thread—it is not the Digital Thread. An analogous example is the Open Systems Interconnections (OSI) Reference Model, a uniform neutral descriptive framework of the configurable underlying concepts common across diverse communication networks and protocols [28]. A Digital Thread generic reference model should be a compact relational framework describing all concepts essential to Digital Threads. This turns out to include multiple types and instances of digital models and other information, about multiple systems with different properties, differentiated by the reference model.

The generic reference model used here is a configurable model-based systems engineering (MBSE) pattern used by the International Council on Systems Engineering (INCOSE). The INCOSE Agile Systems Engineering Life Cycle Management (ASELCM) Pattern describes innovation ecosystems to understand their agility, adaptability, use of underlying information, demonstration of ecosystem-level learning, and overall performance, including obstacles and challenges. INCOSE working groups collaborated to use this reference model in a series of published studies to improve the understanding of ecosystem agility in a systems engineering context [29-33]. In addition, AIAA uses the same reference model in another series of studies of Digital Twins in an aerospace context [3, 34]. While this paper presents the reference model in a conceptual graphic form, it is also implemented as an Object Management Group (OMG) SysML configurable ecosystem model.

The ASELCM Pattern describes the nature and intended purpose, use, application, and benefits of the Digital Thread. It describes the Digital Thread feature embedded in a larger ecosystem context (enterprise, engineering organization, factory, operations setting, etc.) that must be referenced to explain the purpose, expected impact, and value of a specific Digital Thread. Accordingly, the reference model used here is larger in scope than the Digital Thread because it summarizes the (configurable) library of different (ISO 15288) life cycle management capabilities that any given Digital Thread could be expected to serve [35, 36]. Highlights of the ASELCM reference model particularly relevant for improved understanding of the Digital Thread are discussed below.

Reference Boundaries, Capabilities, Interactions, Roles

The ASELCM Pattern logical architecture defines three logical system reference boundaries for the systems engineering life cycle management ecosystem as depicted in Figure 2, and decomposed in Figure 3 and Figure 4 (as Levels 0, 1, and 2, respectively). For the purposes of this paper, these diagrams provide a less formal representation of the equivalent SysML version. Table 1 provides examples of Figure 2 entities:

System 1 is the Engineered System, any system that is subject to research and development, engineering, production, distribution, deployment, utilization, sustainment, and retirement. It includes manufactured products as well as service offerings at any point in their life cycles. System 1 is the “real” system produced and placed into service—not a model of it. (Because System 2 is our main focus for the Digital Thread, to avoid confusion we have omitted the traditional term “System of Interest”.)

System 2 is 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 for observing and learning about System 1 and its environment, not just engineering and deploying it. One instance of System 2 may support many instances of System 1. A Digital Thread for System 1 is a capability within System 2, including users of the Digital Thread. System 2 may contain models of System 1. The generic reference model of the Digital Thread appears in System 3. System 2 direct influence on System 1 is through System 2’s production, distribution, and sustainment. Primary direct consumers of Digital Thread information are System 2 processes.

System 3 is the Innovation Ecosystem, which is the environment with which System 2 interacts across its own life cycle. It includes the life cycle management system 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 engineering and deploying it. The planning and deployment of a Digital Thread for System 1 is a responsibility of System 3. System 3 may contain models of System 2. One instance of System 3 may support many instances of System 2. This AIAA paper is an example of a System 3 activity, as are many other technical society activities intended to improve the understanding and implementation of future System 2’s of the world.

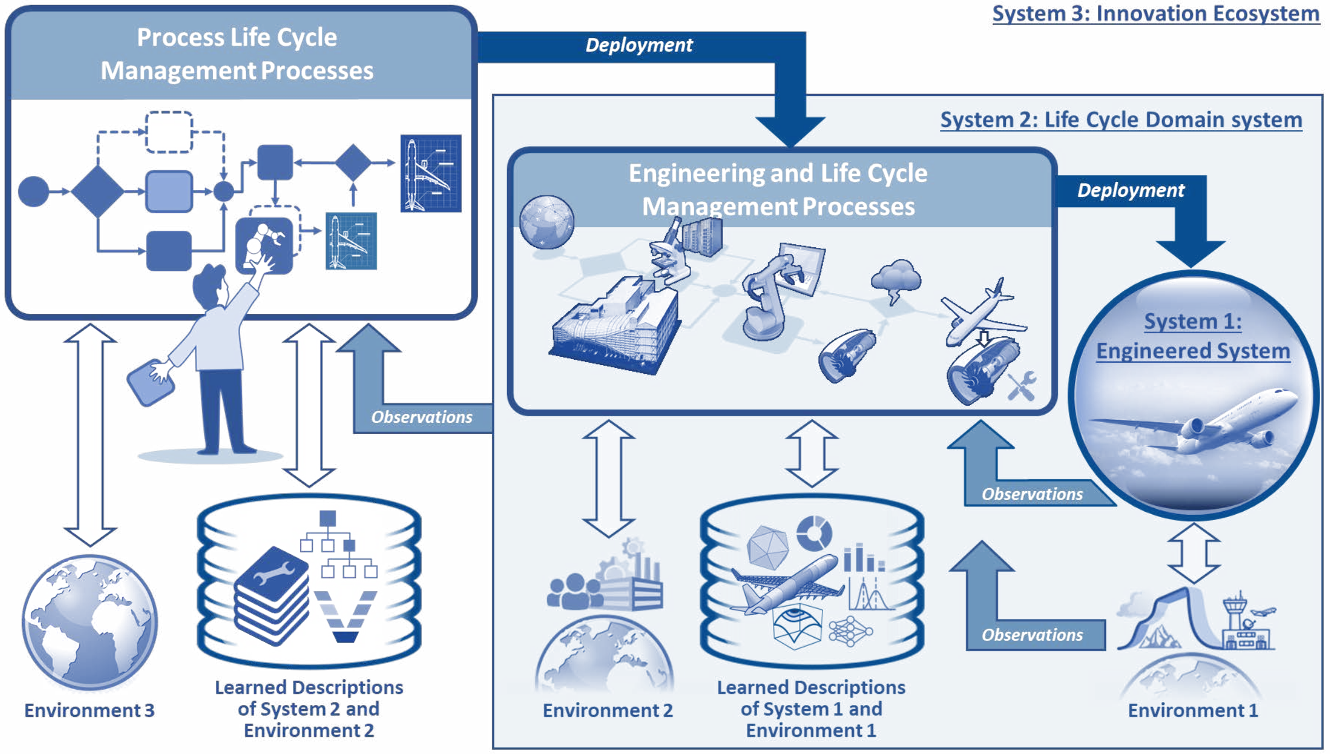


Figure 2. INCOSE ASELCM Level 0 Reference Model—Systems 1, 2, and 3.

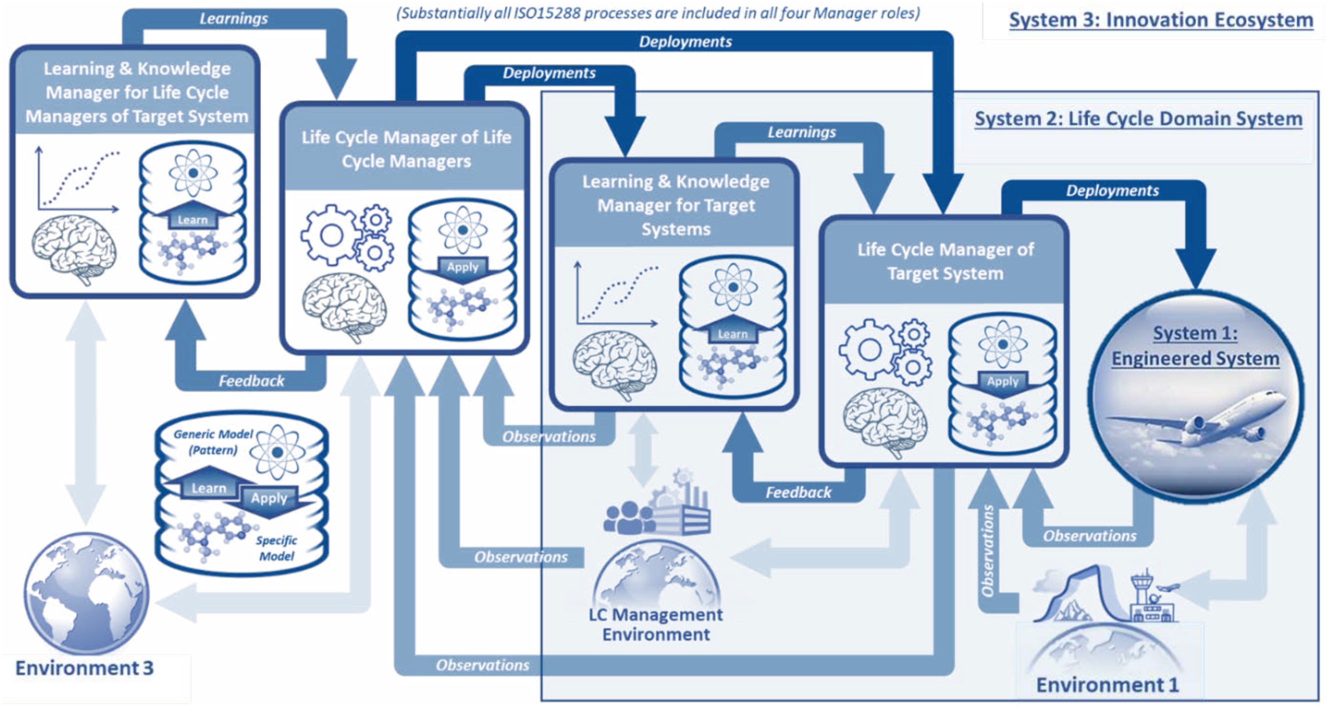


Figure 3. INCOSE ASELCM Level 1 Reference Model—Explicit Learning and Application of Learning.

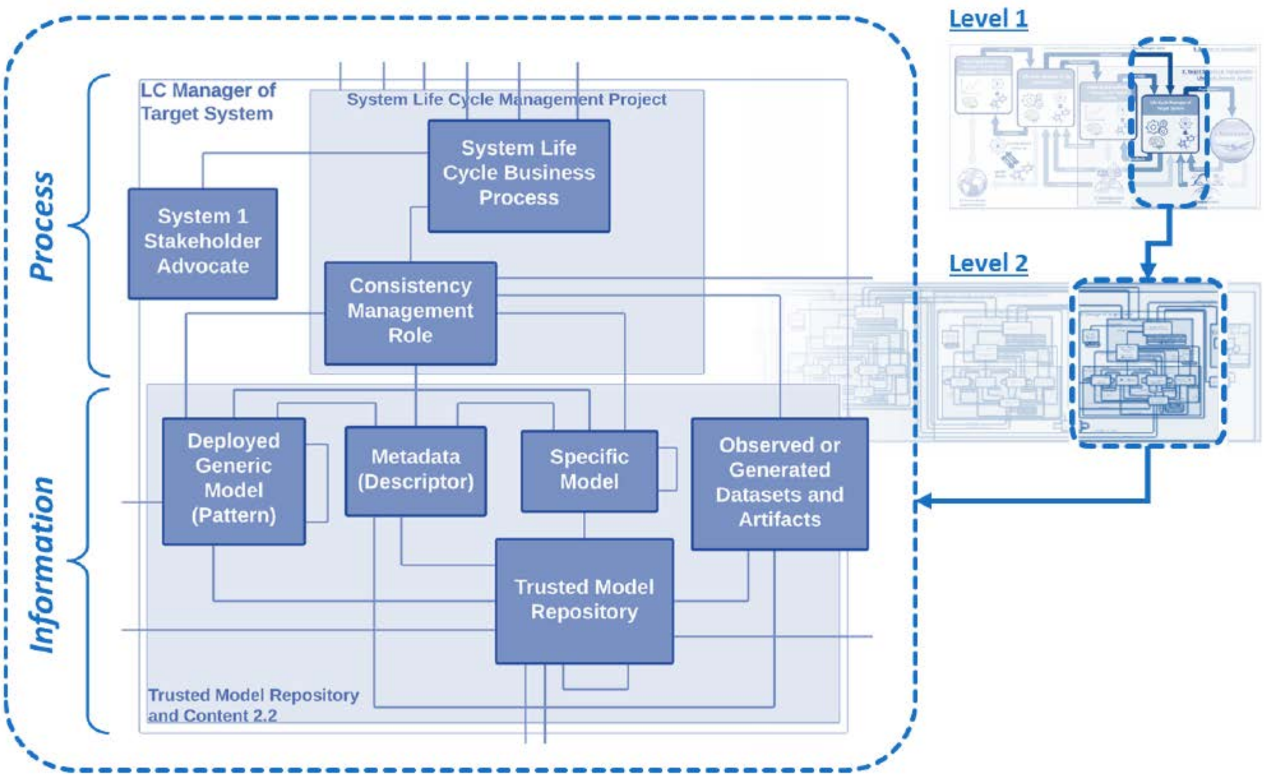


Figure 4. INCOSE ASELCM Level 2 Reference Model—Processes and Information.

Table 1. Examples of Reference Model Level 0 Entities

Reference Model Boundary	**Reference Model Level 0 Entity (Fig 2)**	**Aerospace Examples**
System 1: Engineered System	Engineered System	Aircraft, landing gear subsystem, landing gear component
System 2: Life Cycle Domain System	Environment 1	Airport, weather system, runway, manufacturing floor, maintenance system
	Engineering and Life Cycle Management Processes	Mission engineering, design review, simulation process, manufacturing process, service delivery
	Learned Descriptions of System 1 and Environment 1	Landing gear subsystem requirements, electrical schematics, weather models, landing gear system model, CFD simulation, production recipes, physics, design patterns, personal and tribal knowledge, digital thread describing System 1 product
	Environment 2	Industry funding, job market, pandemic, workplace
System 3: Process Life Cycle Management Processes	Process Life Cycle Management Processes	Program definition process, engineering methods definition, production standards process, engineering education, tooling specification, program analysis, AIAA, INCOSE, IEEE
	Learned Descriptions of System 2 and Environment 2	Enterprise procedures, production job descriptions, organization charts, handbooks, courseware, personal & tribal knowledge, digital thread describing System 2 process
	Environment 3	Methods research, competition, professional and technical societies, engineering educational institutions

The reference model includes over 60 life cycle management capabilities in the form of configurable ecosystem stakeholder features, covering ISO 15288 management capabilities, agile engineering capabilities, and others. While the Digital Thread feature is one of them, almost all the others are enhanced by the Digital Thread feature—for example, requirements management, verification, etc. The KPIs (key performance indicators) of the ecosystem are attributes of this ecosystem stakeholder feature model. Those modeled capabilities describe a set of (neutral, generic, configurable) functional interactions and roles that intersect with the Digital Thread, which supports and advances the enhanced emergent capabilities of the ecosystem. Key aspects are described in the following sections.

System 3 Digital Thread: Planning, Deploying, and Improving the System 2 Digital Thread

The ASELCM pattern permits the study and planning of a pre-Digital Thread environment and its transformation to a Digital Thread environment, including intermediate transitions, local capabilities, and islands in time or functions that are not yet fully connected. Figure 2 and Figure 3 show that the planning, specifying, deployment, and ongoing improvement of the System 2 Digital Thread feature is a System 3 role.

The System 2 ecosystem, the environment of the System 2 Digital Thread, is a complex system of systems and arguably is always more complex than the System 1 that it manages. Accordingly, System 2 Digital Thread capability necessarily requires systems engineering of System 2. That is the role of System 3.

A System 2 Digital Thread capability is subject to its own System 3 Digital Thread, including:

1. Specifying, designing, acquiring, validating, deploying, commissioning, qualifying digital threads
2. Digital Thread transition, in-service observation, sustainment, cycle repeat
3. Planning and supporting a series of releases of System 2 Digital Thread capabilities

It is unnecessary to start from scratch on the above since configuring the detailed ASELCM pattern provides a form of structured analysis using an existing starter pattern.

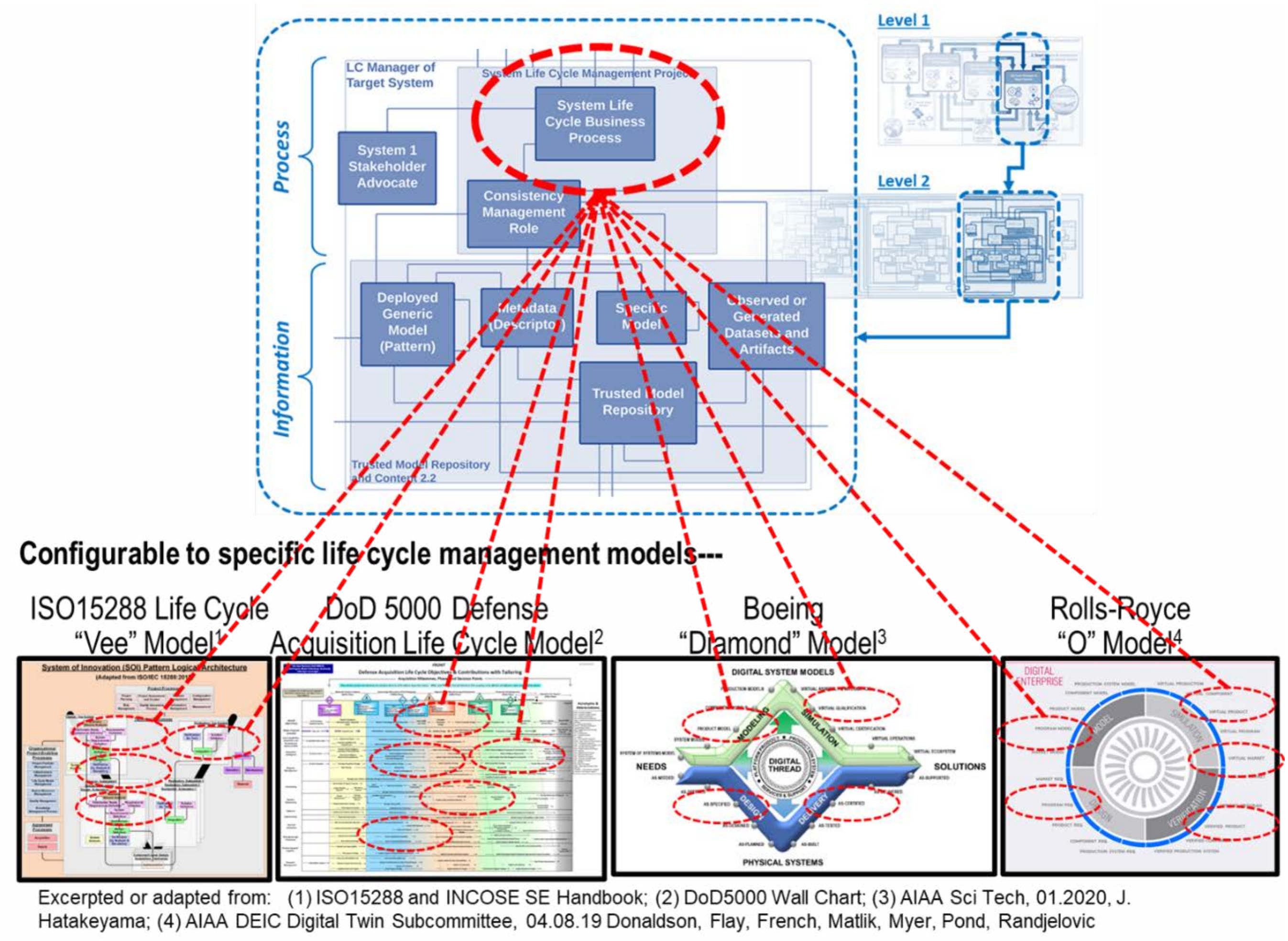
Digital Thread Support for Enhanced Business and Technical Processes

Each enterprise has its own description of its business and technical processes. Figure 5 shows that instances of the Digital Thread reference model's underlying process and information roles interact with each other and with higher-level life cycle management business and technical processes they should serve and enhance—a primary purpose of the Digital Thread. The population of the reference business processes represents a project, enterprise, supply chain, or ecosystem. Typical business process roles would include the life cycle management processes of ISO 15288 but may be enterprise or domain specific. Examples of such processes would be requirements engineering, manufacturing, or sustainment.

The importance of this part of the Digital Thread Reference Model is that it connects a configured set of Digital Thread roles and interactions to the business processes to be supported and enhanced. This simple set of reference connections grounds the planning of a Digital Thread in the processes that it supports. In larger supply chains and ecosystems, this includes crossing inter-enterprise boundaries and considering implied questions of access control to information.

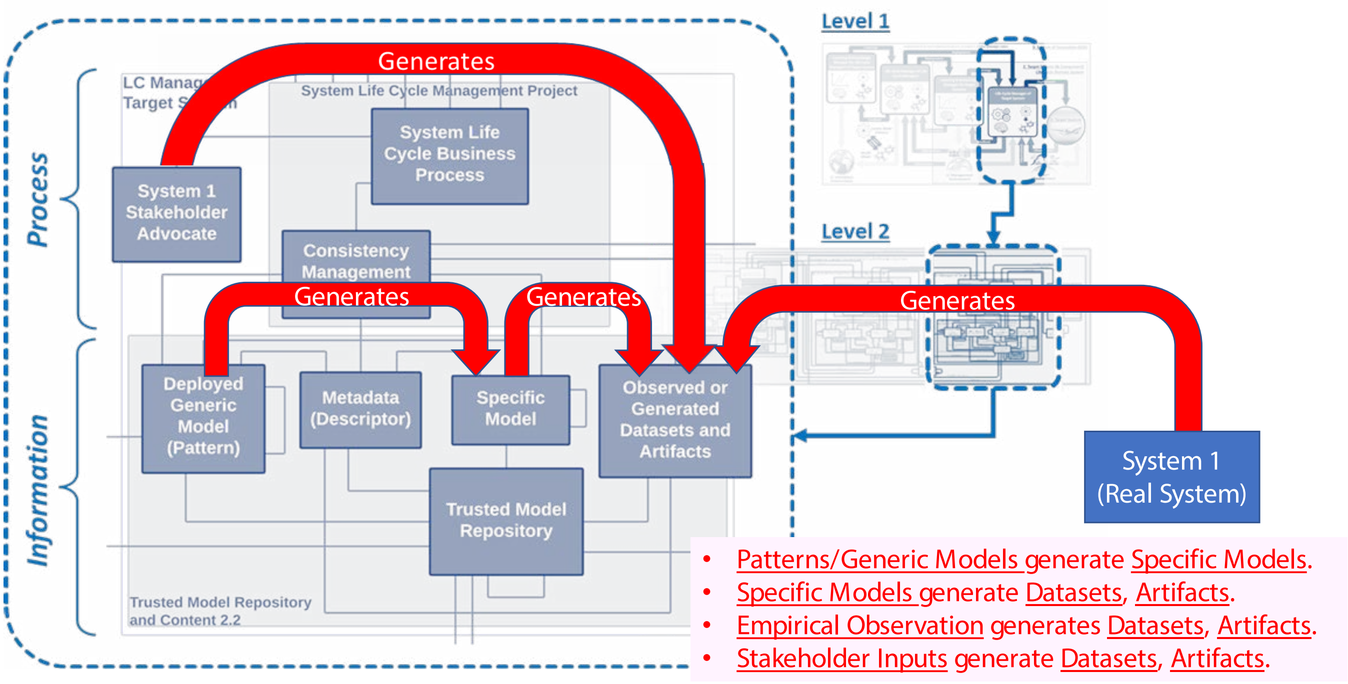
Figure 6 (page 15) illustrates the concept of the class of metadata (descriptor) information in the Digital Thread. When configured into a Digital Thread, this information describes the other classes of information. Large enterprises are awash in tens of thousands of highly diverse digital models, data files, and other information, for which a uniform (but configurable) metadata family is sorely needed [37, 38].

Figure 7 (page 16) illustrates the concept that information in the Digital Thread may originate from stakeholders (e.g., RFPs, requests, etc.), external observations of the System 1 product and its environment, simulations by specific models, or from experience with formal learned patterns or informal tribal knowledge.



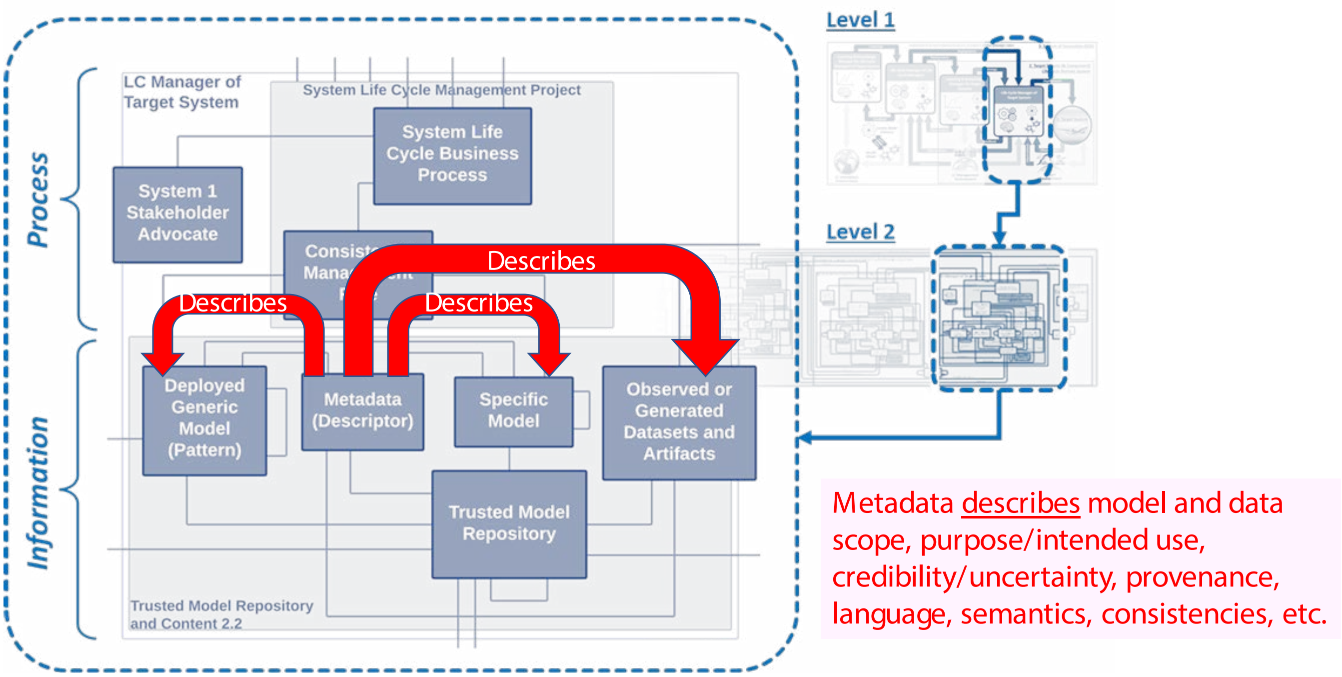
Excerpted or adapted from: (1) ISO15288 and INCOSE SE Handbook; (2) DoD5000 Wall Chart; (3) AIAA Sci Tech, 01.2020, J. Hatakeyama; (4) AIAA DEIC Digital Twin Subcommittee, 04.08.19 Donaldson, Flay, French, Matlik, Myer, Pond, Randjelovic

Figure 5: Configuring reference model business processes supported by Digital Thread to the business processes at hand.



- Patterns/Generic Models generate Specific Models.
- Specific Models generate Datasets, Artifacts.
- Empirical Observation generates Datasets, Artifacts.
- Stakeholder Inputs generate Datasets, Artifacts.

Figure 6. Metadata is the guide to diverse information across the ecosystem.



Metadata describes model and data scope, purpose/intended use, credibility/uncertainty, provenance, language, semantics, consistencies, etc.

Figure 7. Information propagates from external and internal sources.

Consistency Management: A Central Paradigm Advanced by the Digital Thread

The very name Digital Thread calls upon intuitive recognition that there is a form of continuity to the information about a system that emerges during and throughout its life cycle. However, the Digital Thread is about more than merely the historical sequence of that information—it is about the expectations of managing a set of consistencies between what the various information components represent. While an SAE standard [9] describes a set of information artifacts expected over the life cycle of aero parts, the more challenging need is the consistency of what those artifacts describe with each other and with real parts, external entities, and actual performance.

We emphasize that the managed consistencies include the most basic ones of engineering and life cycle management, and not just more recent concerns with digital model interoperability, as described below. Examples of the more basic expected consistencies are answers to the following traditional questions:

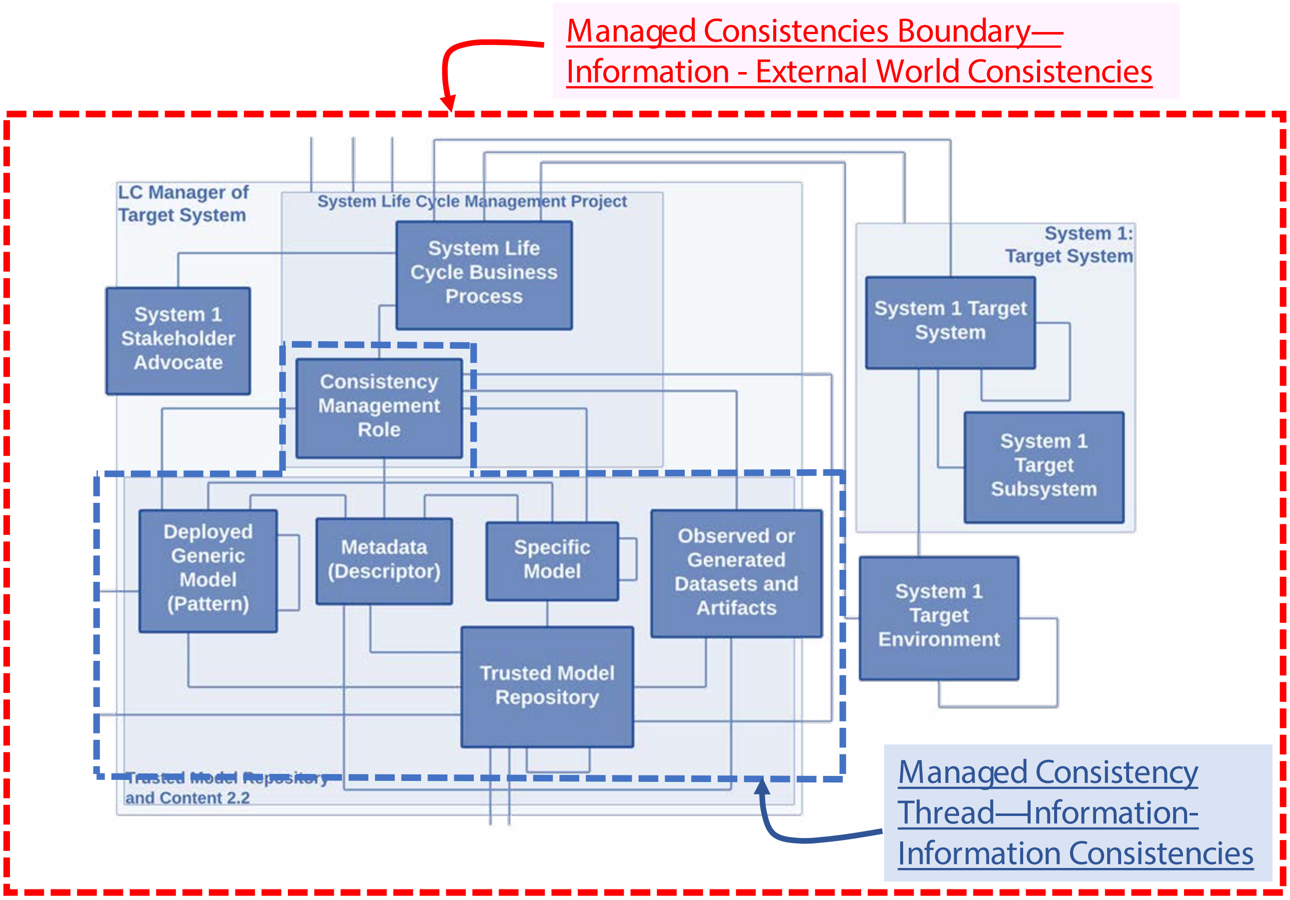
- Is the product design consistent with the product requirements? (Notice the answer can change over life cycle time.)
- Are those requirements consistent with the mission and stakeholder needs and priorities?
- Are the emergent behaviors (both required and to be avoided) in the engineered system consistent with the learned experience about the underlying phenomena from which they emerge?
- Are instances of the manufactured product consistent with the design specifications? Are the customers' uses of the product consistent with the original product mission and requirements?
- Is the performance of the deployed product in the field consistent with the specified requirements?
- Is the environment of use of the product consistent with its representation in the product mission and requirements?

Those and other consistency issues have been an explicit part of engineering and life cycle management for many decades longer than the recent emergence of Digital Thread terminology. Visuals such as the Forsberg Systems Engineering "Vee" [39] diagram, the Boeing "Diamond" [40], the Rolls-Royce "O" [41], and others all illustrate the notions of "threads" of consistency between different information describing the product and its setting. Managing these consistencies may call upon the deep human experience of engineers, project managers, cost analysts, contracting officers, and others. In any case, the emergence of the Digital Thread holds out the promise of improved ability to recognize and manage a long list of important consistencies across the life cycle. Whether these improvements are quantitative (evolutionary within existing approaches) or qualitative (revolutionary by "changing the game") might be arguable, but we assert that at least some of the following can be seen as the latter.

How is improved consistency management to be achieved, and why will the Digital Thread be able to provide it? The reference model supports four consistency management insights that are discussed below. Historically these are areas of intensive human expertise and high effort, as well as high cost of "escapes" (missed inconsistencies). They will also have costs and resource allocations to improve upon as described, but the reference model can help provide clarity for that analysis.

1. **Management, Not Just Information**: Even though the Digital Thread information boundary is in the reference model, this model shows that the more critical boundary to identify is the Managed Digital Thread, indicated in Figure 8 by the dashed lines. The Managed Digital Thread combines the information elements, in the lower half of this diagram, with the consistency management role in the upper half of the diagram. There are many instances of this role, and associated data items, for the different types of consistencies described. This role includes the responsibility to detect and manage consistencies in the information content; the role has more specific names in organizations that must practice requirements validation, design verification, production verification, in-service support, etc. Part of the Managed Digital Thread is about a new environment where these traditional consistency management roles are performed; this is also a reminder that terms like "authoritative source of truth" are oversimplifications. Figure 9 points out three common sources of authority (i.e., T1, T2, and T3), which frequently provide inconsistent information. Consistency managers must constantly reconcile these inconsistencies through requirements relief, design change, production process updates, price negotiation, etc. The first step is recognizing these roles and the associated consistencies in the explicit configured reference model for a given Digital Thread plan. The information within the Digital Thread does not manage itself. The term Managed Consistency Thread is used for the extended system boundary shown in Figure 8, including the information and the consistency management role. A key aspect of planning a Digital Thread is establishing the consistency management roles and their scopes, whether labor-intense (the current state) or more automated (see later below). The Managed Digital Thread makes it clear that the information in the Digital Thread does not manage itself and recognizing that is Insight 1.
2. **Explicating the Consistency**: The reference model also teaches us that metadata in the Digital Thread should explicitly represent the current state of consistency, which is frequently under stress and in flux. Figure 10 of the reference model illustrates the conceptual information model of a Consistency Thread, representing the information that needs to be consistent, the consistency relationships to be managed, and the current state of each consistency. We agree with the conceptual Digital Thread information models such as Hedberg [42] but emphasize that it is crucial to add the consistency status and reconciliation metadata, which becomes a key accounting necessary to manage consistency and its consequences. That record should also include reconciliation actions taken, even if manually, to manage inconsistency as shown in Figure 10. All of those are aspects of the consistency management role. Ultimately this explicit recognition also clarifies the fact that the innovation cycle is itself a dynamical system navigating in the space of these inconsistencies [43]. Accounting explicitly and universally for consistency and its reconciliations in the extended metadata is Insight 2.
3. **Managing Consistency Includes Managing Uncertainty**: The consistency of information is not a simple binary true/false proposition. Many types of consistencies to be managed can involve degrees of uncertainty. Whether in the form of model uncertainty quantification (UQ) [44], credibility assessment frameworks (CAF) [45], or otherwise, making consistency management explicit means that the Digital Thread metadata should include expression of the degree of uncertainty in those consistencies, a task of the consistency management role, and this is Insight 3.
4. **Human-Machine Partners in Consistency Management**: A key promise of Digital Engineering is the vision that, for particular managed consistencies, sufficiently explicit digital data may allow automated or semiautomatic processes to detect or measure inconsistency, if not reconcile it. Familiar examples of achieved detection progress are found in FEA simulations of CAE-designed

part behaviors, compared against digital models of required performance. This assumes management of another consistency—the verification, validation (against empirical experiments or other benchmark criteria), and uncertainty quantification (VVUQ) of model fidelity. But consistency management is also needed higher in the left side of the Vee diagram, as in stronger management of stakeholder-to requirements consistencies, emphasized in agile methods. Examples of "in the wings" automation can be found in the "model checking against patterns" and "model synthesis from patterns" automation described in References [46-49] and [50], using semantic and other technologies. All of these are aspects of the consistency management role. Automating at least part of the management of consistency is Insight 4. In mathematics, consistency as discussed herein is a type of equivalence relationship [51].

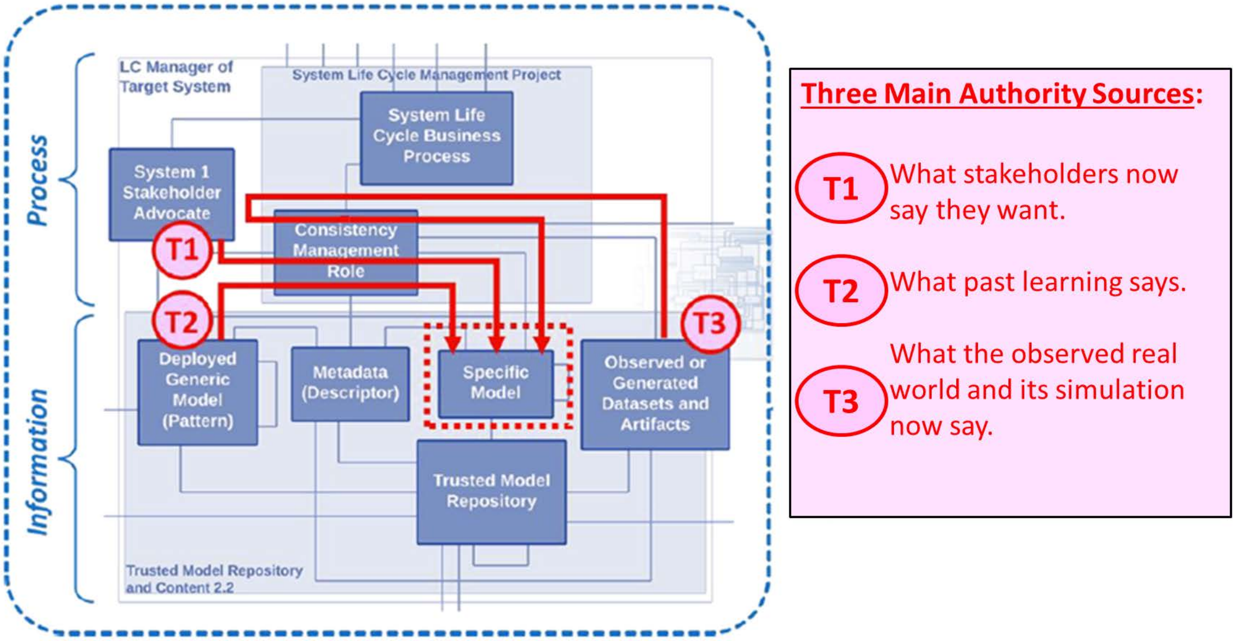


Managed Consistencies Boundary—Information - External World Consistencies

Managed Consistency Thread—Information-Information Consistencies

Managed Consistency Thread System Boundaries

Figure 8. Managed information-external world and information-information consistencies.



Three Main Authority Sources:

T1 What stakeholders now say they want.

T2 What past learning says.

T3 What the observed real world and its simulation now say.

Figure 9. Three sources of authority—often in conflict.

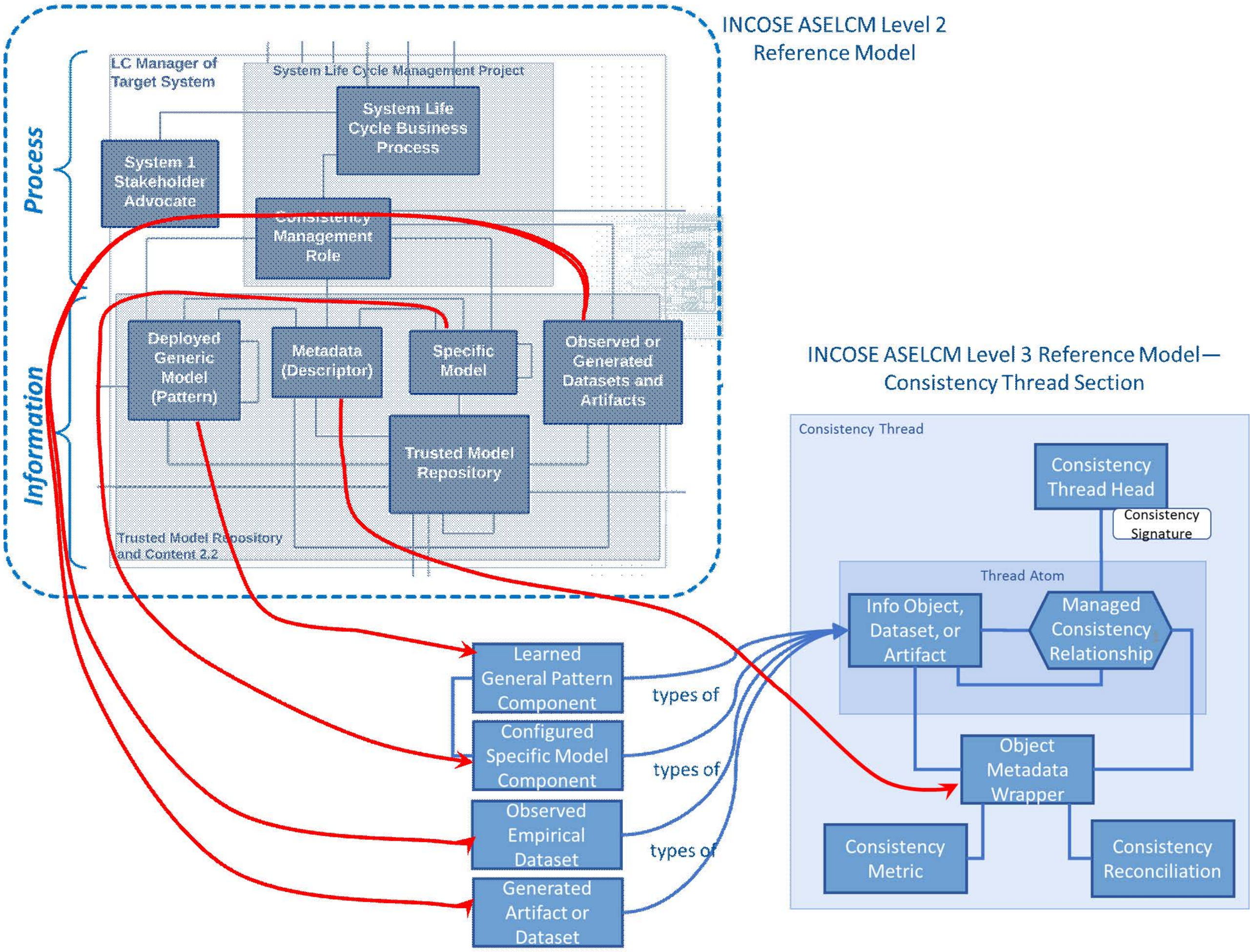


Figure 10. Consistency threads span models, patterns, datasets, and artifacts.

Note that the management of semantic interoperability between information segments is a case of consistency management by System 3, which is responsible for representing the plan for System 2's Digital Thread automation and information about System 1. For example, different information segments involving system requirements, design, production, operation, or sustainment involve different ontologies (named concepts and the framework of relationships between them).

The Digital Thread manages semantic interoperability so that different information elements can be jointly managed for consistency. Semantic interoperability does not necessarily imply that the segments use the same language, tooling, or formal frameworks of conceptual terms and relationships (ontologies). Semantic interoperability refers to whether the semantic mapping between them is sufficient for the consistency management functions. Semantic interoperability includes cross-supply chain boundaries, as the ASELCM pattern includes cross-multi-enterprise ecosystem boundaries. The dynamical growth of the scope and complexity of managed products and their environments means that semantic interoperability questions will arise as managed systems evolve. Relevant standards include ISO 10303 [52] and OSLC [53].

Having these semantic mappings in place allows comparability of the information segments but may still indicate that they are in conflict, as in the example case of sustainment descriptions that conflict quantitatively (but not semantically) with mission availability descriptions. Consistency is required (1) in semantics and (2) in the underlying meaning of what the semantics express. Thus, answering the question "are the requirements satisfied by the design?" might at one time be answered by "we don't know because their descriptions are not semantically consistent enough to determine that." Later, the answer could become "now the semantics are consistent enough to determine the answer, and the answer is that the requirements are not satisfied by the design," so they are still inconsistent—but in a different way.

Group Learning, Generic Threads: Threads for More Than Individual Products

Many conversations about Digital Threads focus on the Digital Thread of individual projects or programs. Like ISO 15288, one sees a description of all the types of information to develop and manage over a life cycle. But not much is heard about "what about what we already know?" Management of balance in acquiring new information versus locating and applying existing information is left for separate consideration. The ASELCM Pattern makes explicit the two aspects by its split of System 2 (Figure 3) into transforming what is known about the product (System 1) and the coupled but separate role of learning what is not known. The Digital Thread should not simply chronicle the fact that a project relearned the hard way what was already known by others in the enterprise. Instead, the Digital Thread should demonstrate the persistence of learning across projects and into more general knowledge where possible.

What do we mean by "persistence of learning?" The perspective of the reference model is that learning is not the accumulation of information but instead improving performance as compared to past experience. Further, by past experience, we are not referring to the same person having the past experience as performing again in the future—instead, we mean the experience of a person or group within the community improving the performance of another part of the community through shared threads of learned patterns. So persistence of learning means improving performance based on experience across time, space, and population. Instead of persistence of accumulated information, it is about how new projects configure their models based on learned pattern updates from past experience (i.e., persistence of knowledge).

The left side of System 2 in Figure 3 is concerned with learning and curating what has been learned for future use. The right side of System 2 is concerned with assuring that the knowledge is applied (e.g., as formal configurable patterns or less formal information assets) for a current project. Learned patterns are IP assets, with their own Digital Thread life cycle management, separate from but coupled to the threads of projects that use them.

The above points offer significant challenges but major rewards. The reference model helps make it clear that the development, propagation, and advancement of patterns as reference architectures, ontologies, standards, and other frameworks is an important path within this effort.

The Generic Reference Model Explains Diverse Instances

A concluding perspective on the value of the generic Digital Thread Reference Model is its unifying common coverage of very diverse instance implementations. For example, the seemingly simple generic directed graph reference model of Figure 10 describes highly diverse instances such as Figure 11 and Figure 12.

Given the Figure 10 Consistency Thread description of the reference model, Figure 11 illustrates the partitioning of the Digital Thread associated with an engine's product life cycle by identifying nine typical domains within the life cycle. The total amount of information describing the engine shown in Figure 11 grows as it is aggregated across the different components (e.g., blade, disk, shaft) and subsystems (e.g., fan, compressor), to the system as a whole (e.g., engine). In that sequence it describes the properties of progressively larger entities, along with traceable dependencies of the larger upon the smaller. The recursive nature (system of systems) of the Digital Thread is represented in Figure 11. The opportunity for full traceability and authorization from its origin to the terminus is illustrated by tracing the engine Digital Thread associated with the compressor, and a given rotor stage within that compressor, to the blades and disk associated with that stage. Then the consistency linkage of information within and between the various domains (compartmentalization) of the individual part's life cycle is revealed. The increase/decrease and intricacies of information content are illustrated by the increase/decrease of the diameter of a given thread and the interweaving of the various threads. Further, each thread has other interdependent threads (e.g., consistency threads, metadata), not illustrated, associated with each life cycle domain. Consequently, the Digital Thread enables the adjudication of whether a digital representation (e.g., compressor) is indeed a Digital Twin or not at any time throughout the life cycle. The presence of the interconnected life cycle domains at the bottom of Figure 11 is intended to imply, at any level of subsystem, the existence of a predecessor/successor Digital Thread, i.e., the evolution in time of the Digital Thread.

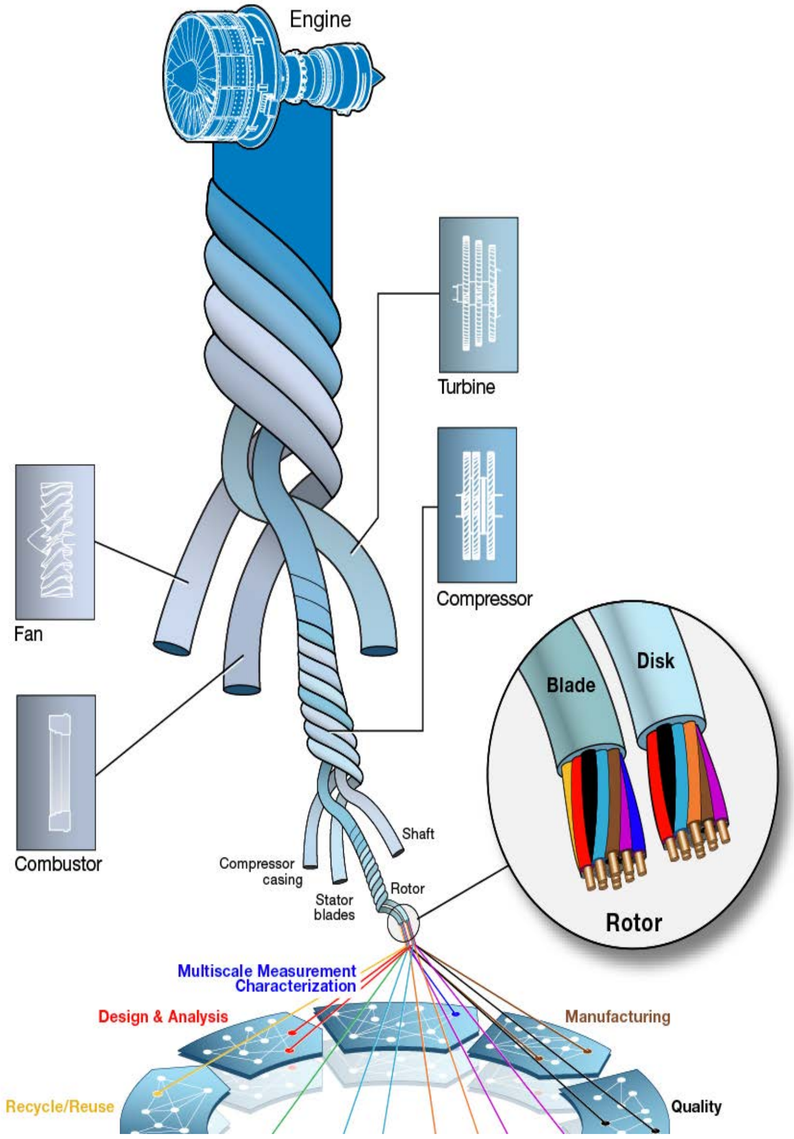


Figure 11. A simplified view of a system's digital thread.

An alternative representation of the temporal Digital Thread is shown in Figure 12. The two-dimensional Digital Thread life cycle domains are shown, emphasizing threads associated with blades (red dots) and rotor (green dots) components called out. The purpose is to illustrate the connectivity of Digital Threads from one life cycle domain (e.g., design and analysis) to another (e.g., multi-scale characterization) and the Digital Thread connectivity within a life cycle domain; e.g., blade one (B11) and blade two (B21) of Generation 1: Compressor. Further, Figure 12 illustrates the predecessor/successor Digital Thread connection concept. Information from Generation 1 (e.g., B11) informs decisions made about Generation 2 (e.g., B12) of a given component or system throughout various aspects of its product life cycle.

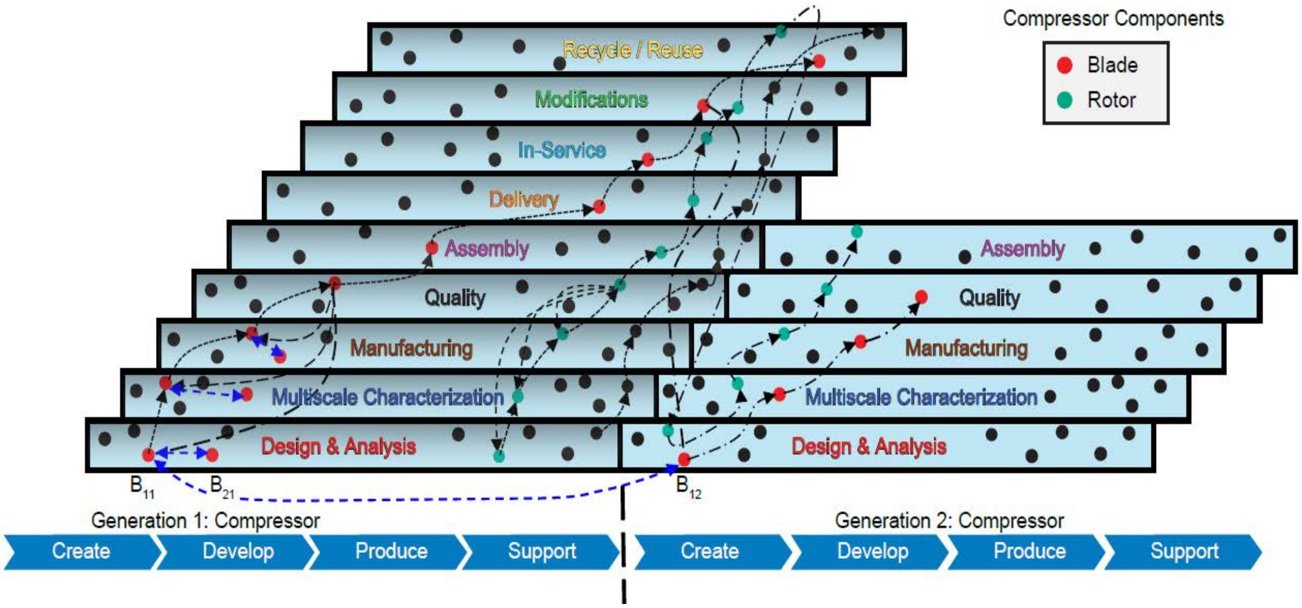


Figure 12. Schematic of Digital Thread evolution and connectivity.

Tailoring to the Aerospace Domain

Regardless of the domain of application, the development, maintenance, and life cycle management of the Digital Thread (including supply chain management across multiple countries and continents) involves a complex collection of systems, processes, and associated data. Alternatively, the degree of complexity, the impact and consequence of failure, and the degree of certification are features that vary significantly across domains (or industries).

Aerospace systems are characterized by a delicate balance between all engineering disciplines, critical interdependencies between software and hardware components, high levels of coupling between thousands to millions of components, and a very high cost of initial development and production. These attributes drive the need for more digital modeling, analysis, simulation, virtual commissioning, and, eventually, digital twins. Furthermore, the complexity that characterizes such systems increases when many diverse systems (e.g., air, ground, and sea) must work together to achieve common objectives. In this context, a system of systems approach is needed to understand, design, produce and sustain these modern systems. This requires the integration/incorporation of many individually complex models of these systems within the Digital Thread.

Throughout the life cycle, product configuration information must be carefully managed to maintain the consistency of the data sources. The maintenance of this critical information enables faster, easier system evolution in response to a quickly changing environment. The Digital Thread ensures product consistency in an environment of change through rigorous configuration and data management. Therefore, the Digital Thread enables shorter life cycle phases and a more responsive design, manufacturing, and sustainment environment. In addition, the numerous components have driven the commercial industry to distribute the supply chain across the entire world, encouraging a worldwide production environment. While this is good for an international economy, it is a problem for national defense aerospace applications since the data, materials, and models may be managed in environments that cannot, for security and sovereignty reasons, know what the final product is or understand their role in the larger system. Conversely, the final system configuration may not have the source data related to the manufacturing processes used to create the system components. The Digital Thread, when properly established on a digital ecosystem platform, facilitates data sharing across the full supply chain, thereby increasing customer confidence in product integrity. Technology like blockchain could further extend the capabilities and data integrity provided across the supply chain.

While aerospace and other industries share a similarity in complexity, the degree of complexity for aerospace is orders of magnitude greater. For instance, the number of parts for an airplane is two orders of magnitude greater than the number of parts in a modern automobile. The level of supply chain management needed to manage this significant delta is challenging enough; however, the interdependencies of the engineered solution, the assembly processes, and change management are exponentially increased by this complexity. Commercial and defense aerospace products are designed and manufactured using rigorous systems engineering processes based on physical and system sciences using specialized systems and tools; however, there are significant differences in their mission requirements and operating environments. Commercial products typically operate in a cooperative environment (e.g., airlines, airports, and traffic management agencies). These models become much more complicated in the defense industry as weapons are included — the numerous types of armaments of a particular airframe drive model fidelity to a whole new level. Thorough integration of numerous subsystems and their models is needed, along with common interfaces shared between very disparate mission sets. Due to mission requirements for both commercial and defense aerospace industries, the cost of failure is potentially human life – the probability of such consequences must be understood and minimized through significant oversight and appropriately managed through rigorous certification processes. The regulations covering aerospace applications are diverse and thorough – and are another multiplier to an already overwhelmingly complex problem space. The differences between the aerospace industry and other industries and between commercial and defense products demand a whole new level of maturity, rigor, and consistency for the Digital Thread in the aerospace industry. As such, the Digital Thread must meet the challenges in safety, quality, performance, scalability, and complexity of both commercial and defense aerospace products, systems, and system of systems.

The aerospace industry, both commercial [54] and defense [55], is learning from the auto industry on how to address the need to accelerate development and capture knowledge. Techniques and methods such as set-based design (SBD) [56-58], combined with multidisciplinary design analysis and optimization (MDAO) [59, 60], become more critical in nonlinear, highly interrelated aerospace systems, where even small changes in one subsystem impact other subsystems and can drive high-level requirements and quality attributes. As such, the combination of these techniques and methods is increasingly necessary for advanced aerospace system design and dramatically scales the linkages in the Digital Thread [61, 62]. This trend is also apparent in other industries such as automotive with high-performance design that are turning to MDAO and using SBD design principles [63, 64]. Roper alludes to the impact of "designing, assembling, testing, even sustaining hundreds of systems digitally before the first parts are bought or metals bent" [65]. Managing these 102 to 109 design variants [65, 66] using the Digital Thread will challenge our emerging digital ecosystems' architectures, implementations, and scale. Indeed, "the complexity of creating a matrix-like Digital Thread for a high-performance military system is a daunting task" [65].

This document has presented a unified aerospace industry/academia/government position on the definition and value of the Digital Thread. The next section discusses recommendations and next steps.

Recommendations for Actions

Adoption of the Digital Thread involves both internal and cross-organizational transformations that must be practical, palatable, phased and incentivized. This paper provides a baseline position and understanding for facilitating the required collaboration efforts across industry, academia, and government. Implementing the Digital Thread within any digital ecosystem to facilitate and impact decision making is paramount to ensuring the digital transformation of a given organization. A broader enterprise benefit realized from the application of the Digital Thread requires a collaborative pursuit of the following four focus areas and activities — business, technical considerations, cultural stack transformation, education/training — for accelerating value creation.

Business Case

Recommendation #1: Establish a business case, tailored to a given organization, as an essential step for adopting the Digital Thread

While the technical imperatives for the need of the Digital Thread are clear, the business case can be built through incremental agile practices. Finance-driven companies find themselves in a Catch-22 situation if they require the Digital Thread to justify the significant investments required to develop the Digital Thread through return-on-investment (ROI) analysis. New business models, such as Eric Ries' Lean Startup model, approach this challenge differently, avoiding the waste generated in classical business planning and ROI analysis when developing new technologies [67]. Although smaller lean and agile businesses have a distinct advantage, the Digital Thread is still needed to identify appropriate metrics to quantify and benchmark product development, adoption, and performance.

In aerospace, the Digital Thread may originate outside the organization developing the product. For example, customers, national laboratories, universities, business partners, and suppliers have originated or supported the product life cycle. These organizations each hold portions of the Digital Thread that must link downstream to the product Digital Thread. Providing an enduring continuity across these organizational boundaries that protects intellectual property and provides cybersecurity requires an aerospace industry strategy and the technical considerations discussed below.

In addition, better cost models are needed if the aerospace industry, especially the defense industry, is to enable one to “bend the cost curve” and thus follow trends in the semiconductor industry or auto industry. This cost modeling is aided by the Digital Thread itself, enabling discovery and traceability for better cost model formation. In addition, anonymized data collected across industries could provide even more utility requiring collaboration and agreements.

One example of ROI is in satisfying environmental regulatory requirements with respect to the European Commission known as REACH (Registration, Evaluation, Authorization, and restriction of Chemicals), wherein companies are obliged to answer a consumer inquiry about the presence of a substance of very high concern in each product within 45 days or suffer penalties. It has been demonstrated that given a robust information management system, such requests can be fulfilled within minutes to hours instead of days, thus saving significant labor and money.

Technical Considerations

While many technical enablers exist at various levels of maturity that could support implementation and enable the effective use of the Digital Thread, such as recent developments in elastic cloud, containerized software, the IoT, and semantic brokering technology, the following three — standards, fidelity and efficiency of model, and automation — are foundational and important for implementing the Digital Thread.

Standards/Best Practices

Recommendation #2: Establish best practices which lead to industry standards for guiding implementation of the Digital Thread Standards form a robust basis for enabling innovation, creativity, and competition. Therefore, appropriate standards to connect different parts of the Digital Thread are needed, including application program interfaces (API) and other data interoperability standards.

The Digital Thread requires new capabilities to support creating, managing, navigating, and analyzing the linkages between entities. Unlike the situation with more established computational tooling, mechanical computer-aided design (MCAD), for instance, as used in the aerospace community has an opportunity to establish genuinely open standards if it acts together and quickly. The business needs, which are subject to network effects, exceed the tooling market’s size alone and suggest that market forces will reconcile current proprietary limitations. Tool vendors who embrace these open standards will be part of the solution. The onus is on the community to work together to realize the full potential of the Digital Thread.

Fidelity and Efficiency of Methods

Recommendation #3: Understand the trade-off between fidelity and efficiency of the methods and methodologies used throughout the Digital Thread to ensure a fit-for-purpose and cost-effective implementation.

While significant advances have been made with MDAO, the ability to conduct large-scale design exploration and optimization at the system level needs development. Therefore, the Digital Thread needs to contend with scale. Developing complex aerospace systems with 104 or more design variables and constraints necessitates continued research in multifidelity modeling methods and system-wide uncertainty quantification (UQ). These methods need to move toward petascale (1015 FLOPS) and exascale (1018 FLOPS) high-performance computing (HPC) national resources. Moreover, as AI/ML is exploited in system design exploration and data analytics, appropriate computer architectures (e.g., GPUs, TPUs, etc.) on the elastic cloud are needed. While these computational requirements relate to the simulation of high-fidelity models and the Digital Twin, the Digital Thread needs to maintain the relationships to a federated set of models that can be executed in a synchronized way. The details of the data architecture will be discussed in an upcoming implementation paper.

Automation

Recommendation #4: To reduce the burden of imposing a Digital Thread framework on the user community, one should minimize the manual capture, linkage, analysis, maintenance, and dissemination of data/metadata through judicious automation.

Although one might assume automation of the Digital Thread is obvious, its importance must not be underestimated. Its practical implementation and buy-in within the user community (at all levels) will require the maximum and judicious chosen degree of automation possible with respect to the capture, linkage, analysis, maintenance, and dissemination of data/meta-data throughout the product life cycle. Without minimizing the burden of entering data along with its appropriate metadata, the implementation, maintenance and thus the utility of the Digital Thread will be compromised by lack of participation by the community it is meant to serve. Consequently, when designing the infrastructure to support the Digital Thread, automation should always be kept at the forefront.

Cultural Stack Transformation – The Hard Part

Recommendation #5: Understand that addressing the cultural barriers to adoption will be more difficult than any technical barrier and should be a primary concern in any implementation plan/initiative.

Technically, digital thread implementation is challenging; however, it pales in comparison to the difficulty in overcoming the cultural change challenges within an organization required to implement the Digital Thread. John P. Kotter points out in Accelerate, "The most fundamental problem is that any company that has made it past the startup phase is optimized much more for efficiency than for strategic agility – the ability to dodge threats with speed and assurance" [68]. History indicates that cultural changes are the most challenging barriers to address regarding the successful creation and implementation of a new paradigm ("culture eats strategy every time") [69].

Referring to the Level 0 reference model in Figure 2, organizations need to transform their System 3 for strategic agility to (1) be able to implement the Digital Thread and (2) be able to respond to needed changes exposed by the Digital Thread. Moreover, using the Digital Thread effectively requires cultural stack transformation (e.g., workforce, organizational hierarchy, governance, best practices, user experience design, etc.). The needed cultural transformation is recognized in the fifth goal of the DOD Digital Engineering Strategy [70], "transform the culture and the workforce to adopt and support digital engineering across the life cycle." The cultural change is especially true for the Digital Thread because the Digital Thread permeates all areas of an enterprise. Consequently, the surgical transformation of the product development system (System 2) is not achievable without a comprehensive transformation of the organization. The rigidity of current (System 3) practices must be transformed for organizations to support and take advantage of the Digital Thread. Additionally, cultural change must be done to garner trust in the organization. As Stephen M.R. Covey points out in The Speed of Trust [71], a lack of trust is a "tax" on our organizations. A robust implementation of a Digital Thread within a digital ecosystem instills trust throughout an organization by granting decision makers, at all levels and throughout a product's life cycle, access to the "right" information, in the "right" format, at the "right" time.

The business and technical needs associated with the Digital Thread require unprecedented cooperation between government, industry, and academia. Therefore, the Digital Twin Center of Excellence proposed in the AIAA Digital Twin Position Paper [2] should be expanded to include the Digital Thread and digital ecosystem for the reasons outlined in that paper.

Education/Training

Recommendation #6: Education and training of a multidisciplinary workforce is imperative to enable full adoption and use of the Digital Thread capabilities.

Fundamental changes in the workforce to support digital engineering are needed. Besides the increasing demand for data analytics, the aerospace workforce must learn to work in engineering development environments (ecosystems) that require what Andrew McAfee and others refer to as "platform thinking" instead of channel thinking [72, 73]. Subject matter experts need to "meet" with their models on a framework to conduct multidisciplinary analysis as the product develops, reducing technical and intellectual debt continually over a project rather than a sudden "big-bang" integration event late in development. Moving from point-based design to set-based design on the Digital Thread presents an entirely new way of thinking about product design enabled by the Digital Thread. Further, there is a need to formalize, nurture, and grow critical skillsets through appropriate training and education of the workforce. The design, development, and full implementation of Digital Threads require engineers to understand their discipline's fundamentals and a strong familiarity with digital tools and environments [74]. Skills at the intersection of many disciplines are also required, including systems engineering, software engineering, machine learning/artificial intelligence, modeling and simulation, database management, digital curation, etc. Unfortunately, these disciplines are rarely taught within the same academic curriculum. To keep tomorrow's workforce current and relevant, new multidisciplinary programs, informed by industry and governmental organizations' needs and insights, should be proposed to encompass the disciplines noted above. Finally, the roles and responsibilities of individuals relative to working within the digital thread framework, in each organization, must be articulated clearly and succinctly.

A coordinated effort facilitated by professional organizations is needed to guide government, industry, and academia in addressing these educational challenges.

Glossary

ASELCM Pattern	The INCOSE Agile Systems Engineering Life Cycle Management (ASELCM) Pattern is a model-based pattern describing an enterprise, program, supply chain, or larger scale ecosystem in which the life cycle of engineered or natural systems plays out. This includes the (human managed or natural) evolution and life cycles of engineered products, systems-of-systems, and sociotechnical systems. The ASELCM Pattern is a reference pattern with a particular focus on group learning, adaptation, and agility in the face of change and competition. The ASELCM Pattern is also known as the Innovation Ecosystem Pattern.
Authoritative Information	Validated from at least one of three traditional sources: stakeholders, empirical observation, or experience. (See Figure 9 and discussion in the Generic Reference Model section)
Authoritative Source of Truth (ASoT)	An authoritative source of truth is an entity such as a person, governing body, or system that applies expert judgement and rules to proclaim a digital artifact is valid and originates from a legitimate source. (from Object Management Group (OMG) MBSE Wiki); see also Figure 9 and discussion in the Generic Reference Model section)
CAE; Computer-Aided Engineering	Computer-Aided Engineering refers to the use of a wide range of automated engineering tools across the different engineering disciplines. These include design tools for the effective and efficient design of mechanical parts, electronic circuits, software, and other elements, as well as the tools used to perform modeling and behavioral simulations. The tooling typically includes automated checks on design rules, libraries of reusable elements, control of documentation and versioning, and other aspects.
Consistency Management Role	In the context of the ASELCM Pattern, a logical role responsible to detect and track the consistency, or inconsistency of certain aspects of an engineered product, its environment and stakeholders, or information about them. This role is also responsible, on behalf of certain System Life Cycle Business Processes, to influence, achieve, or maintain those consistencies, including the reconciliation of detected inconsistencies.

Consistency Management; Consistency	In the context of the ASELCM Pattern, consistency management means the attention given across the life cycle of a managed system product for tracking, achieving, and maintaining consistency between different targeted aspects of the managed system. Consistency management is the abstract framework term used to describe a wide range of traditional engineering and life cycle management issues such as the consistency of system design and system requirements; the consistency of system design and production; the consistency of system use and requirements; etc. The ultimate aim of consistency management is to reduce inconsistencies across the life cycle to acceptable levels.
Consistency Thread	In the context of the ASELCM Pattern, a managed collection of information organized to describe the history, current status, or planned future of an Engineered System of Interest, including all aspects relevant to its life cycle management. This is all with a special emphasis on the consistency of certain aspects of that information with each other or external entities. A Consistency Thread is the conceptual precursor to a Digital Thread, and does not assume digital technology, instead representing both past and future life cycle management practice.
Cultural Stack	In the spirit of technology stack, the cultural stack is defined as a hierarchy of cultural issues within and across sociotechnical systems. Some cultural issues are very pervasive and foundational, some are more singular and specialized.
Deployed Generic Model (Pattern)	In the context of the ASELCM Pattern, a model that is sufficiently general that it can be used to generate more specific configured models. For example, an architectural framework, product line model, or S*Pattern.
Digital Thread	The Digital Thread is a collection of linked authoritative4 digital information pertaining to a process, product, or system, whose consistency is actively managed throughout the life cycle. This enables accessibility, traceability, currency, applicability, and credibility of information, thus facilitating the capture, communication, and use and reuse of knowledge to efficiently inform decisions that realize value.
Digital Twin	Short definition: A Digital Twin is a virtual representation of a connected physical asset. Detailed definition: A set of virtual information constructs that mimics the structure, context and behavior of an individual / unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value.
Engineered System (System 1)	In the context of the ASELCM Pattern, a system whose life cycle is managed (whether explicitly by humans or implicitly by its environmental interactions). Typically, it is a manufactured product, service, sociotechnical system, or part of the natural world.

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4 Three sources (stakeholders, experience, and observations) of authority are defined and discussed in the Generic Reference Model section (see Figure 9).

FEA; Finite Element Analysis	Finite Element Analysis refers to the (typically automated by computer algorithms and tools) use of discretized numerical algorithms to compute mechanical or other static or dynamic performance of mechanical or other parts, materials, and designs. The general idea behind these tools is to convert a continuous (e.g., partial differential equation) first principles physics model to an approximation over finite intervals of space and time.
INCOSE	The International Council on Systems Engineering, a technical professional society for systems engineering.
Innovation Ecosystem (System3)	In the context of the ASELCM Pattern, the system in which the life cycle of systems plays out naturally or with human management, from the earliest concepts of the system, through its engineering, production, delivery, use, sustainment, retirement, and improvement.
KPI; Key Performance Indicator	Key Performance Indicators are characteristics or variables identified as the main stakeholder measures of performance for some targeted aspects of a system.
Life Cycle Domain System (System 2)	In the context of the ASELCM Pattern, the system in which an Engineered Product will perform, including all the actors (external systems) with which that Engineered Product will interact over its life cycle, from its earliest to last life cycle stages.
Metadata (Descriptor)	In the context of the ASELCM Pattern, a data structure that describes information about a model, pattern, or data set. This metadata provides a kind of label on otherwise complicated information entities to explain their nature, intended purpose, provenance, credibility, and other aspects and to assist in their planning, discovery, exchange, assessment, and use. For example, a configured instance of the Model Characterization Pattern (MCP).
Model	A model is a simplified representation of a system at some particular point in time or space intended to promote understanding of the real system. As an abstraction of a system, it offers insight about one or more of the system's aspects, such as its function, structure, properties, performance, behavior, or cost [75]. In the context of a Digital Thread, it could be assumed that models are digital formal technical descriptions in the languages of engineering, science, or mathematics. In a larger context, not all models are necessarily formal, digital, or in those languages.
Observed or Generated Datasets and Artifacts	In the context of the ASELCM Pattern, empirical data from measurements of external System 1 instances, environments, stakeholder data, simulations, reports and documents, or other artifacts and datasets.
Ontology	In the context of information technology, ontology refers to domain-specific reference frameworks of meaning, consisting of defined classes, the relationships that may occur between them, and their properties. Ontologies are similar to reference architectures that establish semantics for the domain they are about. A complete formal ontology establishes what statements may be made about a domain.
Pattern; Model-Based Pattern	Something that recurs over time, space, or other index, with at least similar content. Model-Based Patterns describe those recurrences, including their fixed and variable (configurable) parts, using modeling languages and data structures.

RFP; Request for Proposals	As a part of an acquisition process, a commercial notification requesting bidders to generate proposals / quotations to supply specified goods or services.
SAE International	A professional technical society concerned with automotive, mobility, and aerospace domains, including the establishment of related technical standards.
Semantic Interoperability	If models of a certain type are interpreted by human or machine agents for certain agreed upon purposes, then those interpreting people or machine agents are said to be semantically interoperable if they interpret a given model to have the same, or at least a consistent, meaning. See also "Semantics".
Semantics; Model Semantics	Semantics refers to meaning. In a context involving models, the semantics of a model are the rules for a model should be interpreted by people or automated agents using the model for a given purpose.
Specific Model	In the context of the ASELCM Pattern, a formal data structure that describes some aspect of a modeled thing. The term "specific" in this context means that it may have been derived/configured from a less specific (more general) Deployed Generic Model (Pattern). Specific models may include numerical simulations, descriptive MBSE models, schematic or geometric representations, artificial neural networks and machine learning models, and others.
Simulation	The execution or use of a model [76]. "A model that behaves or operates like a given system when provided a set of controlled inputs." [76]
System 1 Stakeholder Advocate	In the context of the ASELCM Pattern, a person or organization responsible or selected to represent the interests of a System 1 stakeholder group concerned with a System. Such a representative is consulted or observed to understand and plan an Engineered System.
System Life Cycle Business Process	In the context of the ASELCM Pattern, one of the (numerous) business processes concerned with managing various aspects and stages of the life cycle of an engineered system of interest. A typical listing of such system life cycle management processes can be found in ISO 15288 or the INCOSE Systems Engineering Handbook that is based on that standard.
SysML (System Modeling Language)	A standards-based modeling language for representing system-level information about systems of any type or domain. The language was defined by joint activity of the International Council on Systems Engineering (INCOSE) and the Object Management Group (OMG), which maintains that standard, supported by and implemented in the commercial third-party modeling tools of several suppliers. Refer to "OMG Systems Modeling Language (OMG SysML™) Specification", Version 1.6, Object Management Group, 2019, at https://www.omg.org/spec/SysML/1.6/PDF.
Trusted Model Repository	In the context of the ASELCM Pattern, an automated storage and access system containing and making available persistent copies or services of Specific Models, Deployed Generic Models (Patterns), Observed or Generated Datasets and Artifacts, or Metadata (Descriptors), on a secure and trusted basis.

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