INSIGHT

This Issue's Feature:

Digital Engineering

Digital Thread Exploration in Syndeia shows SysML v2 model elements accessed via standard REST/HTTP API

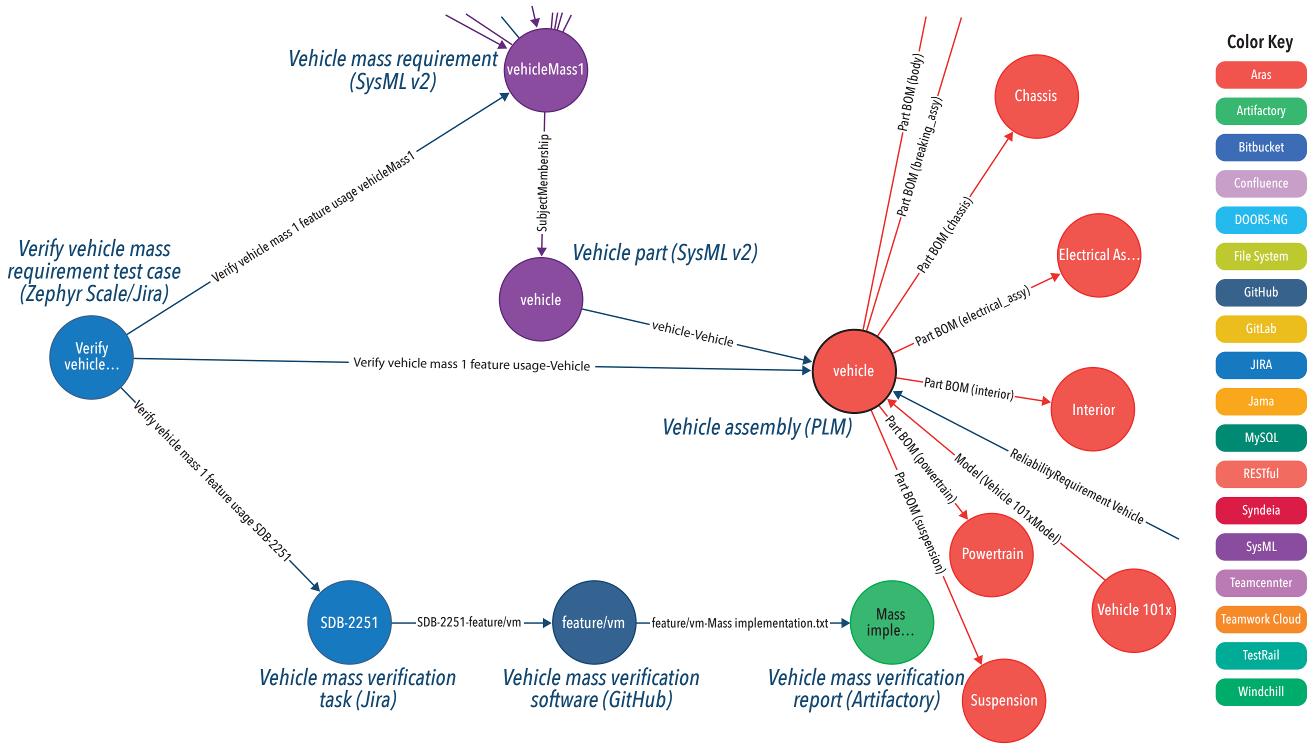

Illustration credit: from the article *Systems Modeling Language (SysML v2) Support for Digital Engineering* by Manas Bajaj, Sanford Friedenthal, and Ed Seidewitz. (see page 19)

MARCH 2022
VOLUME 25 / ISSUE 1

INCOSE

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

Systems Engineering: The Journal of The International Council on Systems Engineering

Call for Papers

The *Systems Engineering* journal is intended to be a primary source of multidisciplinary information for the systems engineering and management of products and services, and processes of all types. Systems engineering activities involve the technologies and system management approaches needed for

- definition of systems, including identification of user requirements and technological specifications;
- development of systems, including conceptual architectures, tradeoff of design concepts, configuration management during system development, integration of new systems with legacy systems, integrated product and process development; and
- deployment of systems, including operational test and evaluation, maintenance over an extended life cycle, and re-engineering.

Systems Engineering is the archival journal of, and exists to serve the following objectives of, the International Council on Systems Engineering (INCOSE):

- To provide a focal point for dissemination of systems engineering knowledge
- To promote collaboration in systems engineering education and research
- To encourage and assure establishment of professional standards for integrity in the practice of systems engineering
- To improve the professional status of all those engaged in the practice of systems engineering
- To encourage governmental and industrial support for research and educational programs that will improve the systems engineering process and its practice

The journal supports these goals by providing a continuing, respected publication of peer-reviewed results from research and development in the area of systems engineering. Systems engineering is defined broadly in this context as an interdisciplinary approach and means to enable the realization of successful systems that are of high quality, cost-effective, and trustworthy in meeting customer requirements.

The *Systems Engineering* journal is dedicated to all aspects of the engineering of systems: technical, management, economic, and social. It focuses on the life cycle processes needed to create trustworthy and high-quality systems. It will also emphasize the systems management efforts needed to define, develop, and deploy trustworthy and high quality processes for the production of systems. Within this, *Systems Engineering* is especially concerned with evaluation of the efficiency and effectiveness of systems management, technical direction, and integration of systems. *Systems Engineering* is also very concerned with the engineering of systems that support sustainable development. Modern systems, including both products and services, are often very knowledge-intensive, and are found in both the public and private sectors. The journal emphasizes strategic and program management of these, and the information and knowledge base for knowledge principles, knowledge practices, and knowledge perspectives for the engineering of systems. Definitive case studies involving systems engineering practice are especially welcome.

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The journal will accept and review submissions in English from any author, in any global locality, whether or not the author is an INCOSE member. A body of international peers will review all submissions, and the reviewers will suggest potential revisions to the author, with the intent to achieve published papers that

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- advance the state of knowledge of the field; and
- conform to a high standard of scholarly presentation.

Editorial selection of works for publication will be made based on content, without regard to the stature of the authors. Selections will include a wide variety of international works, recognizing and supporting the essential breadth and universality of the field. Final selection of papers for publication, and the form of publication, shall rest with the editor.

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A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

MARCH 2022 VOLUME 25 / ISSUE 1

INCOSE

Inside this issue

About This Publication

INFORMATION ABOUT INCOSE

INCOSE's membership extends to over 19,000 individual members and more than 200 corporations, government entities, and academic institutions. Its mission is to share, promote, and advance the best of systems engineering from across the globe for the benefit of humanity and the planet. INCOSE charters chapters worldwide, includes a corporate advisory board, and is led by elected officers and directors.

For more information, click here:
The International Council on Systems Engineering
(www.incose.org)

OVERVIEW

INSIGHT is the magazine of the International Council on Systems Engineering. It is published four times per year and features informative articles dedicated to advancing the state of practice in systems engineering and to close the gap with the state of the art. ***INSIGHT*** delivers practical information on current hot topics, implementations, and best practices, written in applications-driven style. There is an emphasis on practical applications, tutorials, guides, and case studies that result in successful outcomes. Explicitly identified opinion pieces, book reviews, and technology roadmapping complement articles to stimulate advancing the state of practice. ***INSIGHT*** is dedicated to advancing the INCOSE objectives of impactful products and accelerating the transformation of systems engineering to a model-based discipline.
Topics to be covered include resilient systems, model-based systems engineering, commercial-driven transformational systems engineering, natural systems, agile security, systems of systems, and cyber-physical systems across disciplines and domains of interest to the constituent groups in the systems engineering community: industry, government, and academia. Advances in practice often come from lateral connections of information dissemination across disciplines and domains. ***INSIGHT*** will track advances in the state of the art with follow-up, practically written articles to more rapidly disseminate knowledge to stimulate practice throughout the community.

PERMISSIONS

ARTICLE SUBMISSION

insight@incose.net

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- September 2022 issue – 1 July 2022
- December 2022 issue – 1 October 2022
- March 2023 issue – 2 January 2023

For further information on submissions and issue themes, visit the INCOSE website: www.incose.org

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FROM THE EDITOR-IN-CHIEF

William Miller, insight@incose.net

We are pleased to announce the March 2022 *INSIGHT* issue published cooperatively with John Wiley & Sons as the systems engineering practitioners magazine. The *INSIGHT* mission is to provide informative articles on advancing the practice of systems engineering and to close the gap between practice and the state of the art as advanced by *Systems Engineering*, the Journal of INCOSE also published by Wiley. The issue theme is digital engineering. We thank Stephanie Possehl, Acting Deputy Director for Engineering, Office of the Under Secretary of Defense for Research and Engineering and Philomena (Phil) Zimmerman, Deputy Director, Engineering Tools, and Environments at the United States Department of Defense for their unwavering commitment to make this issue possible; theme editors Frank Salvatore and Tracee Gilbert; and the authors for their contributions.

Your editor appreciates the contributions of the authors from professional experience in the mid 1970s shepherding a collaborative, consolidated Bell Laboratories horizontal and vertical vision of evolving the Bell System in the 1980-1990 decade, transforming an analog, electro-mechanical, manually intensive telecommunication service to an integrated digitally engineered, software defined Network of the Future. Key findings included economic, velocity, and security benefits "sellable" in the context of a highly constrained regulatory environment across federal, state, and municipal government agencies. Sound familiar to the imperatives for the current digital engineering initiative? The general Bell Labs Research and Systems Engineering (R&SE) budget line funded the Network of the Future initiative, not beholden to specific development organizations or their corporate oversight.

Stephanie Possehl, Philomena Zimmerman, Tracee Gilbert, and Frank Salvatore lead off with "On the Road with Digital Engineering." The United States Office of the Under Secretary of Defense for Research and Engineering (OUSD (R&E)) launched its strategy to introduce digital engineering in 2018. This was a catalyst to modernize engineering practice across the spectrum of DoD activities by transforming engineering capabilities to drive agility, innovation, and efficiency into engineering practice. Since that time, the DoD, and our Military Services, government agencies, industry, academia, and international partners are implementing digital engineering. The authors provide a historical perspective of how the digital engineering concept evolved and offer insights on lessons learned.

"Digital Engineering Measures; Research and Guidance" by Tom McDermott, Kaitlin Henderson, Alejandro Salado, and Joseph Bradley describes research conducted by the Systems Engineering Research Center (SERC) in collaboration with a government/industry Digital Engineering Measures Working Group creating the first formal measurement framework for this transformation. Their article describes the research, formation of a causal measurement model, and initial specification of candidate measures.

"Systems Modeling Language (SysML v2) Support for Digital Engineering" by Manas Bajaj, Sanford Friedenthal, and Ed Seidewitz highlights how the Object Management Group (OMG) Systems Modeling Language (SysML) v2 and the new standard Application Programming Interface (API) enable MBSE and digital engineering.

"Being Digital: Why Addressing Culture and Creating a Digital Mindset are Critical to Successful Transformation" by Jason Rafoth and John Forsythe states that transformation can only happen when technology and culture are in lockstep, emphasizing the criticality of the digital DNA of the organization.

"Constructing an Authoritative Source of Truth in a Changing Information Landscape" by Tyler Smith, Charles Payne, and John Shackleton describe their work in support of the U.S. Army Mission System Architecture Demonstration to determine requirements, best practices, and available tool capabilities for building and maintaining an Authoritative Source of Truth (ASoT).

Michael Toriello in "Creating the Digital Thread" describes approaches to creating the digital thread, including detailed explanations of trace link properties. He explains an example digital thread from a sample United States Army program and offers guidance for creating and using digital threads.

Axel Reichwein in "Distributed Cross-Domain Link Creation for Flexible Data Integration and Manageable Data Interoperability Standards" offers a strategy to provide a more flexible, user-friendly approach for engineers to specify cross-domain links between different domains of engineering data, which is key to achieving traceability across different product lifecycle phases. A new type of API that allows API clients to find link targets easily and create links makes this possible.

"Realizing the Value Promise of Digital Engineering: Planning, Implementing, and Evolving the Ecosystem" by William Schindel summarizes an aid to analyzing and understanding, planning, implementation, and ongoing improvement of the Innovation Ecosystem or its components. It is based on a generic ecosystem analysis reference model with focal viewpoints. Represented as a configurable model-based formal pattern created by the INCOSE MBSE Patterns Working Group, it was initially applied in a related INCOSE collaboration project led by the Agile Systems Engineering Working Group. Aspects of the resulting framework have subsequently been elaborated and applied in the context of a wide variety of commercial and defense ecosystems across different domains. This includes the ecosystem preparation of internal and supply chain human and technical resources to effectively consume and exploit digital information assets, not just create them. The ecosystem model carries its own representation of enhanced capability implementation by generation of agile release train increments, along with evolutionary steering based on feedback and group learning.

"Digital Twin: Reference Model, Realizations, and Recommendations" by members of the AIAA Digital Engineering Integration Committee (DEIC) addresses the development of standardized methodologies to unleash the full potential of digital twins and increase their adoption across a wider range of disciplines and applications. The authors present 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. The authors introduce real-world examples of aerospace digital twin use cases and discuss how the generic reference model supports the various use case applications. Finally, they discuss recommendations and next steps on how to realize value more broadly from digital twins.

"Versatile Test Reactor Open Digital Engineering Ecosystem" by Christopher Ritter, Jeren Browning, Peter Suyderhoud, Ross Hays, AnnMarie Marshall, Kevin Han, Taylor Ashbocker , John Darrington, and Lee Nelson hypothesize using digital engineering principals to reduce risk and cost and gain schedule efficiencies in the design of a 300-MWt sodium-cooled fast reactor. This ecosystem was deployed to over 200 engineers and used to deliver the conceptual design of the virtual test reactor (VTR). Initial results show significant reductions in user latency (1000x at peak use), the possibility of direct finite-element-analysis (FEA) integrations to computer-aided design (CAD) tools, and nuclear reactor system design descriptions (SDDs) that can one can fully link throughout design in data-driven requirements-management software. Early results have led to the VTR program maintaining milestone performance during the COVID-19 pandemic.

"Digital Engineering Measures Correlated to Digital Engineering Lessons Learned from Systems Engineering Transformation Pilot" by Mark Blackburn, Tom McDermott, Benjamin Kruse, John Dzielski, and Tom Hagedorn discusses analysis that correlates digital engineering success measure (DESM) categories with lessons learned benefits observed during the NAVAIR Surrogate Pilot that applied digital engineering (DE) methods and tools using an authoritative source of truth (ASoT) by modeling everything to demonstrate the art-of-the-possible. The analysis correlated ratings from 17 lesson learned categories to 22 DESMs grouped into four metrics categories.

"Acquirer Driven Digital Engineering Transformation" by Kevin Robinson and Tommie Liddy discusses the benefits and challenges of adopting digital engineering in the concept phase, where the project costs are committed. It highlights that the greatest return on investment for digital engineering is during concept phase as the flow of authoritative information permeates the remainder of the lifecycle. This presents the case for acquisition agencies to both drive the application of digital engineering within their industry and lead by example, through adoption.

We hope you find *INSIGHT*, the practitioners' magazine for systems engineers, informative and relevant. Feedback from readers is critical to *INSIGHT*'s quality. We encourage letters to the editor at insight@incose.net. Please include "letter to the editor" in the subject line. *INSIGHT* also continues to solicit special features, standalone articles, book reviews, and op-eds. For information about *INSIGHT*, including upcoming issues, see https://www.incose.org/products-and-publications/periodicals#INSIGHT. For information about sponsoring *INSIGHT*, please contact the INCOSE marketing and communications director at Marcom@incose.net.

Editorial of *INSIGHT* Special Feature

On the Road with Digital Engineering

Stephanie L. Possehl; **Philomena Zimmerman**; **Dr. Tracee Gilbert**; and **Frank Salvatore**

■ **ABSTRACT**
The United States (US) Office of the Under Secretary of Defense for Research and Engineering (OUSD (R&E)) launched its strategy to introduce digital engineering in 2018. This was a catalyst to modernize engineering practice across the spectrum of the US Department of Defense (DoD) activities by transforming engineering capabilities to drive agility, innovation, and efficiency into engineering practice. Since that time, the DoD, and our Military Services, government agencies, industry, academia, and international partners are implementing digital engineering. This paper provides a historical perspective of how the digital engineering concept evolved and offers insights on lessons learned.

■ **KEYWORDS:** digital engineering, department of defense, strategy, implementation, policy, guidance

INTRODUCTION

Digital engineering is transforming the way the DoD conceives, designs, builds, delivers, trains with, and sustains its capabilities. The Department is implementing digital engineering to drive agility, innovation, and efficiency by harnessing the power of digital practices across the full spectrum of DoD activities.

DoD began its journey to improve simulation-based acquisition, traditional modeling and simulation, and model-based practices. It continued forward as Industry 4.0 began to transform manufacturing practices worldwide. These building blocks provided the foundation, and a community of practice approach has been critical to the success of developing the digital engineering concept, strategy, and implementation. The community of practice includes DoD leadership, industry, academic, and interagency and international stakeholders that have been partners in this journey. This paper will provide context by describing the historical perspective timeline shown in Figure 1.

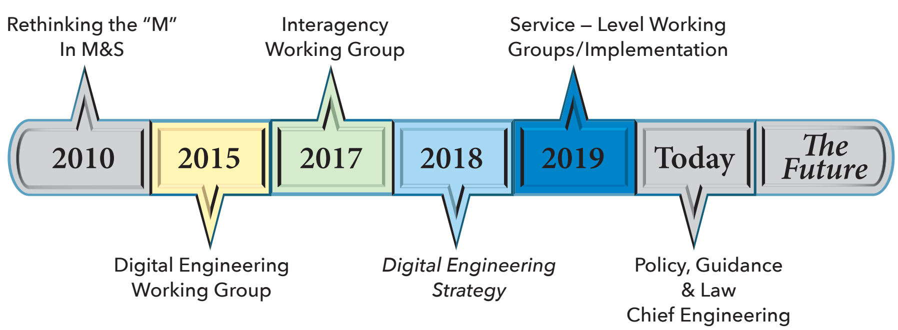

Figure 1: History of DoD digital engineering efforts

The journey began in 2010 when the DoD Systems Engineering office engaged with subject matter experts in the modeling and simulation community to provide recommendations on the near-term opportunities that could advance the use of modeling and simulation within the acquisition process. The Ubiquitous Modeling and Simulation Study (or "The Summer Study") coalesced ideas from Army, Navy, and Air Force organizations. In 2010, as today, there was ongoing work in numerous places for a plethora of programs. The Summer Study viewed challenges not as obstacles but as motivation for innovative thinking.

The study participants observed that modeling and simulation had progressed to become a highly valuable tool, and traditional "M&S" practice had arrived; however, one of the major findings of the study was to rethink the "M" in "M&S" and encourage the use of both physical models and computer-based modeling. Th model-based engineering (MBE) and model-based systems engineering (MBSE) work of the National Defense Industrial Association (NDIA) and International Council on Systems Engineering (INCOSE) inspired this thinking.

Along with the advances in modeling and model representation that drove the finding to rethink the "M" in "M&S" came increased access to advanced computational capabilities (speed, compute power, and visualization). These advances turned out to be the perfect partner that the engineering community needed to reassert its demand for engineering tools that enabled rigor, supported better understanding of risk, and avoided using unnecessary resources.

As this thinking coalesced into a grassroots movement, the establishment of the DoD Digital Engineering Working Group (DEWG) followed in 2015. The purpose of the DEWG was to explore transitioning traditional acquisition processes to a digital model-centric environment. During this time, Industry 4.0 had revolutionized manufacturing practices. Industry 4.0 inspired the scope of digital engineering to extend beyond just model-based engineering approaches that often focused on a particular discipline or aspect (model-based design, manufacturing, testing) to encompass the broad spectrum of models as a continuum across the life cycle of project activities.

In addition to the full-spectrum perspective, Industry 4.0 inspired a focus on data, incorporating advancements in technology (artificial intelligence/machine learning, cloud computing, Digital Twin, and more), and the supporting infrastructure and environment needed to implement digital engineering. The result was a vision for an end-to-end digital enterprise that connects people, machines, systems, processes, models, and data. The DEWG evolved from a small group supporting the development of the digital engineering concept, to an engaging community across the Military Services, government agencies, industry, and academic partners. Through this collaborative forum, the concept continued to mature.

In 2016, the DoD and NASA investigated the impacts and unintended consequences of model-based techniques across organizations. To provide evidence of the benefits, DoD and NASA decided to collaborate on a project – NASA's pathfinder effort for the Model-Based Sounding Rocket Program. The effort offered a high-success-rate mission with shorter life cycle with benefits comparison and quantification against the traditional methods. Interest in digital engineering grew during this time, and engagement with an advisory body composed of engineering leads from the DoD and other federal government agencies, the Interagency Working Group (IAWG) for Complex Systems, ensued. In 2017, the IAWG developed five expectations that engineers could convey to management about the value of using digital model-based techniques within organizational practices:

1. Enhanced communication
2. Informed decision making through increased transparency and greater insight
3. Increased confidence that the capability will perform as expected

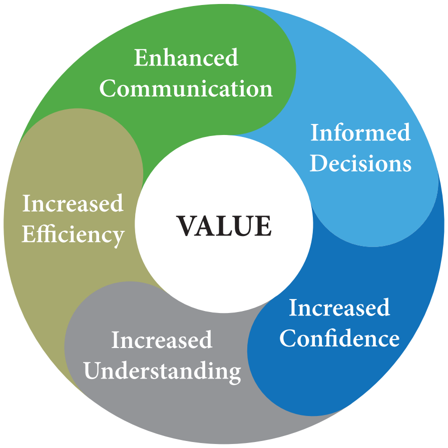

Figure 2: Value of using digital model-based techniques

4. Increased understanding for greater flexibility/adaptability in design
5. Increased efficiency in practices and processes

As the DEWG and its activities matured, DoD instantiated definitions, developed an initial vision for digital engineering, and developed a Defense Acquisition University continuous learning module to evolve the concept.

In June 2018, OUSD(R&E) released the *Digital Engineering Strategy*. This strategy set a vision for innovation across the DoD engineering practice to support life cycle activities. As DoD stakeholders began to implement the strategy, its effectiveness grew as did the potential for success in digital engineering practice. The writing, approval, and release of the strategy was the culmination of a series of studies, efforts, and technology advances. The *Digital Engineering Strategy* presented five goals:

1. Formalize the development, integration, and use of models to inform enterprise and program decision making
2. Provide an enduring, authoritative source of truth
3. Incorporate technological innovation to improve the engineering practice
4. Establish a supporting infrastructure and environments to perform activities, collaboration, and communicate across stakeholders
5. Transform the culture and workforce to adopt and support digital engineering across the life cycle

As requested by the Services, the strategy did not address how to implement digital engineering. Rather, the strategy serves as a method for communicating this evolution in engineering practice. This seemed very practical advice; the Military Services were responsible for the execution of the *Digital Engineering Strategy*. Through many parallel and interconnected efforts, the Department continues to work through challenges on the journey to improve ideas and find the synergies between implementations to advance the most effective digital engineering approaches.

Currently, DoD is developing digital engineering policy and guidance to encourage and support further adoption of digital engineering. OUSD(R&E) is in the initial stage of developing a new issuance on digital engineering implementation. This issuance addresses responsibilities across DoD Organizations (OUSD(R&E), OUSD(A&S), Services) and discusses procedures for implementing digital engineering.

The *Engineering of Defense Systems Guidebook* includes guidance on digital engineering practices involved in the development of DoD systems. The *Systems Engineering Guidebook* includes digital engineering guidance and recommended best practices for defense acquisition programs. The Digital Engineering Body of Knowledge is also under construction. It includes an interactive environment for stakeholders to digitally navigate through knowledge content. The knowledge content provides a set of concepts, terms, examples, lessons learned, and activities identified by and for the community of practice.

Additional updates to existing policy and guidance will continue, as the DoD becomes more deliberate in its transition to digital engineering practices. As we continue as a community, more activities in policy, guidance, infrastructure development, talent management, and more, will be enabled by requirements in law, in community demands, and in technology advancements.

The success of the DEWG and the *Digital Engineering Strategy* provided a focal point and organizing framework for the DoD and its partners to progress toward common goals for widespread implementation. Service-level working groups are driving implementation within the Services. Digital engineering continues as a journey. Technology enables continual evolution of digital practices, and organizational culture and human behavior continue to promote innovative thinking. We must continue to engender a culture of innovation and modify our behaviors to benefit from that innovation.

ON THE DIGITAL ENGINEERING HIGHWAY

The world is in motion, and so is the engineering practice. Evolution, modernization, and progress is like driving on a multi-lane highway in the engineering practice world. We stay in our lanes and make progress, but we know other lanes are available to us to slow down or speed up as our progress demands. We must be able to move forward, pull over, reassess, remerge, and continue. We learn as we go. We must be a community of innovative thinkers that is not afraid to try, fail fast, and improve. We must be willing to be simple and basic in our innovation as well. Sometimes we take a wrong turn, or we get redirected. We need to be accepting of the new direction. Foremost, we must encourage our leadership and workforce to embrace the risk of failure. This perspective views failure as a positive learning step on the road toward ultimate success. We must also be willing and able to smooth out those bumps in the road. We must hold ourselves accountable, and we must be able to measure our results so that we can understand where we have made progress and where we need to still make progress.

In all this change, the idea of "doing digital engineering because it is digital engineering" is one area we need to smooth over. It is imperative that we know the benefit that we will gain. Digital practices are foundational elements to other activities, foundational to other uses. Digital engineering is there to support, with rigor, transparency, accuracy, and history – other disciplines. Digital engineering is not something separately accomplished from the activities it supports. It is a different and innovative way of approaching those activities.

It is also critical that we move beyond labels of subject matter expertise. Digital engineering must seamlessly merge with another lane – the DoD's traditional "M&S" community. We are more alike than different. "M&S" has a long, and rich history of support to many communities in addition to the engineering community. Over time, however, the demand for "M&S" from engineering has faded. As demand fades, so may innovation. In this motion-filled engineering world, we need to take advantage of the well-honed practices that developed in the "M&S" community (validation, verification, and accreditation). The harmonization of these communities is necessary to advance digital practices and modernize "M&S" so that we, and our products, can benefit. We need to look to the standards, the formats, the practices, and the definitions that support the "M&S" community and use them to advance this larger community.

Digital engineering provides the ability to share digital artifacts from one stage, phase, life cycle element, or program to another. There is an opportunity not to restrict use based on the title of the artifacts – as labels are artificial to the reuse activity. While most projects "proceed" from left to right, digital artifacts do not observe any start or end of the stage or life cycle phase. The artifact may have multiple potential applications, and the labels used to describe the digital artifacts such as "training simulation," "mission-analysis data," or "gaming visualization" application often comes after use. Labels cause us to restrict how we might reuse those digital artifacts.

Equally critical is to move beyond the labels of our tools and consider the basic nature of their construct. Consider the similarities, and even the sameness, of architecture and models. In a basic definition, a model is a representation of reality. An architecture is a description and arrangement of things, a description of the relationship between things, and a description of the behavior of things, that is, a description of reality. The parallel between models and architecture is a cultural adjustment that we can and must realize. While we can think of every architecture as a model, not every model is an architecture. Architectures are so much richer than basic models and bring useful dimensionality into the modeling arena. If part of the value of models in digital engineering comes from their availability for computational consumption, then architectures can realize the same value. Once we think of architectures as models and form them in a computationally consumable format, their use will span a variety of activities that model-based techniques support.

On this digital engineering highway, "models" and "model use" are not unique to engineering or to a particular engineering discipline, domain, or activity. The same is true for simulators and simulation use. As use of digital practices spreads into other disciplines, domains, and activities, it is imperative that we allow, and in fact, depend on the commonality of goals to unify the digital practices across the areas of use, rather than allow it to continue to isolate us from each other. Tools are separate from the content that the tools operate on. Visualization tools are useful in a variety of applications; it is the content that makes the visualization tool applicable to a particular activity. By recognizing this, we share in the advances of other communities' digital practices. This innovative thinking connects us.

We must be wary of staying in one lane for the entire trip of digital practice evolution; but we do not want to be all over the road either, which can cause negative consequences! Specializations within a practice provide the opportunity for establishing the specific form, fit, and function of methods, processes, and tools that make sense to a particular community (washing machine, automobile, aircraft); customer (veterans, senior citizens, schoolchildren); activities (patient care, sustainment, travel) and more. However, left unconstrained, specializations will drive us to domains, disciplines, and communities that are isolated, and we will lose any idea of sharing practices. It is imperative that the specialized communities establish common elements that will increase value of digital execution to them, and then look beyond the lane they are in. Common elements of standards, formats, tools, or more, come together to increase adoption and relevancy across all lanes of digital practice implementation. The simple but powerful nature of "digital" is one of those fast lanes that will get us farther down the road, faster.

As we come to understand the reach of digital engineering practices to support all our activities, even those beyond engineering, we remind ourselves that the modernization journey is never complete. We should not fear the discovery. We should embrace innovation as the nature of engineering. We should encourage and help our peers, our workforce, and our leaders understand the evolution as a part of the engineering culture. We should embrace engineering innovation, including progress beyond digital engineering. We should value and understand innovation to be indicative of a world in motion. With this ongoing innovation, we engineer solutions for a better world. ■

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Digital Engineering Measures: Research and Guidance

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ABSTRACT
Digital Engineering and Model-Based Engineering continue to grow in adoption across the systems engineering community. However, programs and enterprises still struggle to quantify the value of this digital transformation. Research conducted by the Systems Engineering Research Center in collaboration with a government/industry Digital Engineering Measures Working Group is creating the first formal measurement framework for this transformation. This article describes the research, formation of a causal measurement model, and initial specification of candidate measures.

Systems continue to grow in complexity, and with that growth comes greater difficulty in managing the development of these systems (DiMario, Cloutier, Verma 2008). The use of models to design systems is increasingly considered a principle of good system design (Bahill and Botta 2008). Model-Based Systems Engineering (MBSE) is "the formalized application of modeling" to the systems engineering process (Friedenthal, Griego, Sampson 2007). As an emerging field, the MBSE literature and earlier SERC research activities cite many benefits organizations can expect to achieve if the approach is implemented properly. However, evidence shows little attention to formally measure these benefits (Henderson and Salado 2021). Systems engineering as a discipline has difficulty providing quantifiable evidence of its value, although those familiar with the systems engineering process attest to intuitively understanding its benefits (Honour 2004). Transitioning from a document-based to a model-based approach to systems engineering represents a substantial financial investment, and organizations want to know if the effort and cost to adopt MBSE is worth it. Transitioning from a document-based to a model-based approach to systems engineering also provides additional opportunity to measure the value of the systems engineering process in ways that were difficult in previous practices.

Digital Engineering (DE) and model-based approaches are two components of enterprise digital transformation that have great promise to improve the efficiency and productivity of engineering activities, particularly for complex engineered systems. Core to this transformation is the integration of data and models across disciplines, often called the Authoritative Source of Truth (ASOT). Also critical to this transformation is a shift from document-based activities to model-based activities as a basis for information flow across disciplines and stakeholders. *The core concept in DE transformation is the use of evolving models and associated data as the primary source of knowledge about a system and its life cycle, continually managed across all the development and management teams*. Systems engineering use of DE is rapidly maturing the "digital system model" as a central resource to manage data and models in the ASOT, supplying integration across discipline-specific data and models. This is a change from simple engineering with models (a standard practice today) to the use of a central set of architectural models that inform and manage all engineering decisions. An emerging international standard codifies this relationship: ISO/IEC/IEEE DIS 24641 Systems and Software engineering — Methods and tools for model-based systems and software engineering (MBSSE).

The Systems Engineering Research Center (SERC) engaged with government and industry subject matter experts (SMEs) to fill the value measurement gap by proposing a set of metrics that should be employed to best show the value of DE and MBSSE. Since there are many potential benefits, we developed a causal model based on performance measurement literature to systematically decide on which metrics should be prioritized, then worked with the community of SMEs to refine that model into a set of potential measurement specifications. In the process, we evaluated the causal model using both literature reviews on DE measurement and discussions with selected enterprises and program offices. The primary contribution of this research is the measurement model, as actual quantitative measurement of DE and MBSSE remains at an early stage, and few concrete examples exist. At this point the research indicates 1) DE and MBSSE have measurable benefits, 2) DE/MBSSE measures can be defined and tracked, and are extensions to well-known software measures, and 3) DE/MBSSE measures primarily support the systems

Table 1. Direct Benefits of DE/MBSSE

Direct Benefits	Definition
Higher level support for automation	Use of tools and methods that automate previously manual tasks and decisions
Early Verification and Validation (V&V)	Moving tasks into earlier development phases that would have required effort in later phases
Reusability	Reusing existing data, models, and knowledge in new development
Increased traceability	Formally linking requirements, design, test, etc. through models
Strengthened Testing	Using data and models to increase test coverage in any phase
Better Accessibility of Information (ASOT)	Increasing access to digital data and models to more people involved in program decisions
Higher level support for automation	Using data and models to support both the integration of information and system integration tasks
Multiple viewpoints of model	Presentation of data and models in the language and context of those that need access

engineering process and can provide data-driven quantitative assessment of systems engineering benefits, given an appropriate measurement framework. This article describes the development and maturation of that measurement framework.

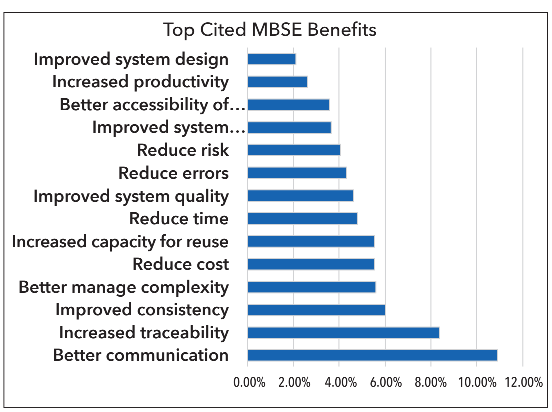
DE and MBSSE have measurable benefits: Previous research on benefits and metrics in DE surveyed both literature and the MBSE community to broadly collect potential measures associated with benefits and adoption indicators (SERC SR-001 2020; SERC TR-002 2020). The survey results and initial DE Metrics report remain available on the SERC website: https://sercuarc.org/results-of-the-serc-incose-ndia-mbse-maturity-survey-are-in. An eventual DE measurement framework should focus on measurement of the primary benefits of DE and MBSSE as well as adoption factors which often serve as leading indicators to these benefits. The most highly cited benefits, enablers, and obstacles are in Figure 1.

The earlier surveys were used to narrow down a set of eight direct benefits associated with DE measurement, as described in Table 1. These benefits were developed into a causal measurement model that found the causal relationships and secondary benefits associated with these primary benefits. These direct benefits form the roots of the causal model, considered as core activities in DE and MBSSE that lead to measurable benefit. From these direct benefits stem the secondary benefits which are the effects/result of these, including those potential metrics that are typically of interest to managers and other stakeholders such as reduced cost, improved quality, or reduced cycle time. The causal analysis informed DE metrics design.

Figure 2 (next page) contains the full causal model. One can visualize the complexity of the measurement challenge from this map. The eight primary benefits are in the top of the map in green boxes and font. All secondary benefits stem from these. In the map the black nodes relate to benefits and the blue nodes relate to adoption factors. Note that the adoption factors form a causal loop beginning with "Projects/Programs use methods and processes" in the bottom left of the figure.

There are three primary factors related to increased stakeholder involvement that are central to adoption. These are in blue boxes and font at the top-center of the map: *greater use of tools, project methods and processes*, and *people willing to use the tools*. Many of the other benefits of a digital transformation will be lost if artifacts must be produced and activities must be conducted outside of the digital environment and related models. Enterprise and program terminologies/ontologies and associated digital libraries are essential to creating the ASOT and adopting a model-centric approach. Both "number of people willing to use DE/MBSSE tools" and "number or percentage of models/data sets in the ASOT" are critical leading indicators of successful DE transformation.

The causal model found a set of base measures in the DE/MBSSE domain that are common to most digital transformation activities and well described in the software community. These include *reduced errors/defects, reduced effort*, and *reduced time*. The causal model also shows that *reduced rework* and *reduced cost* will be important secondary measures associated with these base measures. The causal linkages between these stand out down the center left of the map. Reduced cost, which is the ultimate measure of return, is a lagging indicator dependent on all these other indicators. Reduced cost is an important measure, particularly



Top Enablers	Top Obstacles
Leadership Support	Organizational Culture
People willing to use MBSE tools	Workforce Knowledge/ Skills
Workforce Knowledge/ Skills	Leadership Support
Demonstrating Benefits/ Results	Awareness of MBSE Benefits

Figure 1. Top Benefits and adoption factors from previous research

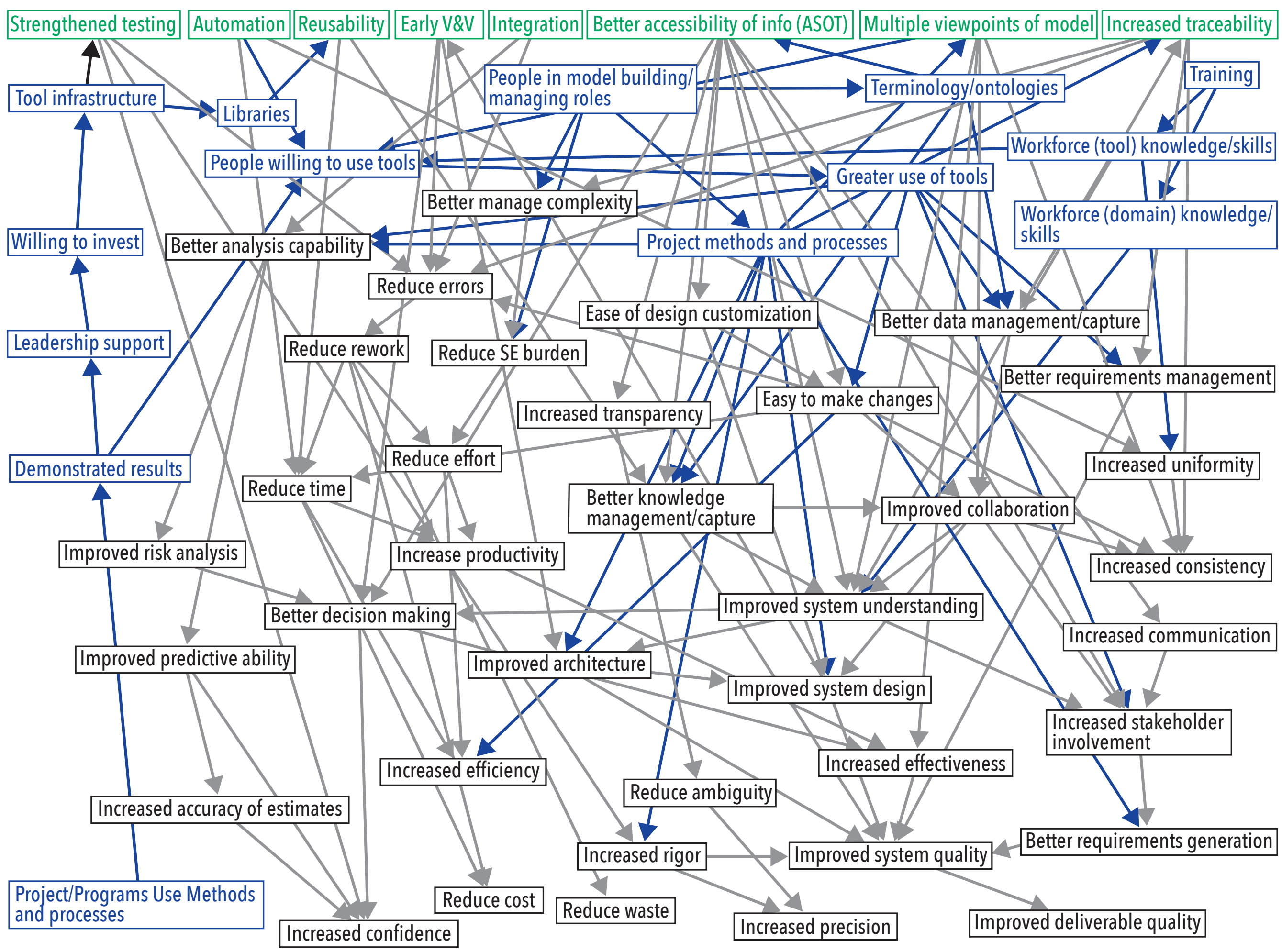


Figure 2. *Full causal model*

across programs in the enterprise, but more leading indicators such as defects and effort also require tracking within a program or project.

In reviews with the SME community, a key aspect of DE/MBSSE is to improve functional completeness and correctness of the underlying description of the design. The ability to quantify and analyze functions in a digital systems model is causally related to the direct benefits of *Early V&V, Strengthened Testing, Better Support for Integration*, and *Increased Traceability*. All these again decompose to base measures of reduced errors/defects, reduced effort, and reduced rework. The DE community should put more effort in defining models associated with decomposition of capabilities, functions, and requirements, then measuring the peer review, simulation, and test of those models.

Another area of interest in the SME community is the efficiency gained in model-based review artifacts. Causally, these relate to the *Better Accessibility of Information* and *Multiple Viewpoints of Model* primary benefits. In this case, *improved collaboration* is the most central secondary benefit. Improved collaboration is difficult to measure directly but is an important user experience metric to assess via surveys of other means in the transformation process. Key related quantitative measures include reduced errors/defects and reduced rework, and how one tracks these measures from phase to phase of the review and decision process. The core product-related measures are defect resolution by phase and rework that must be done or travelled to later phases. Leading indicators associate with number of review discrepancies/actions and decision signoffs or approvals at the review.

Another primary benefit area is *Higher Level of Support for Automation*. Central to automation are number of people willing to use DE/MBSSE tools (automation should increase this), easy to make changes, reduced effort, and reduced time. *Reusability* is a final primary benefit and is most causally related to better knowledge management/capture. Knowledge management is traditionally a difficult area to measure. In DE/MBSSE the causal linkage is from program terminologies/ontologies and associated digital libraries, to reuse of data and models, to better knowledge management/capture.

DE and MBSSE measurement framework: The causal model supported the development of a framework and measurement information model for the specific work performed in the domain of DE and MBSSE. The framework describes the DE/MBSSE unique work one is to measure, and the model describes both the information needs and measures that would allow the performance of that work to undergo evaluation. DE and MBSSE have three interrelated goals: the transformation of engineering activities to fully digital infrastructure, artifacts, and processes; the use of data and models to improve the efficiency and productivity of engineering practice; and the use of MBSSE to fully integrate systems data and models with engineering, program management, and other domains and disciplines. DE/MBSSE work activities are a set of methods, processes, and tools for the life cycle definition, development, and sustainment of complex engineered systems. DE creates not only the product itself, but

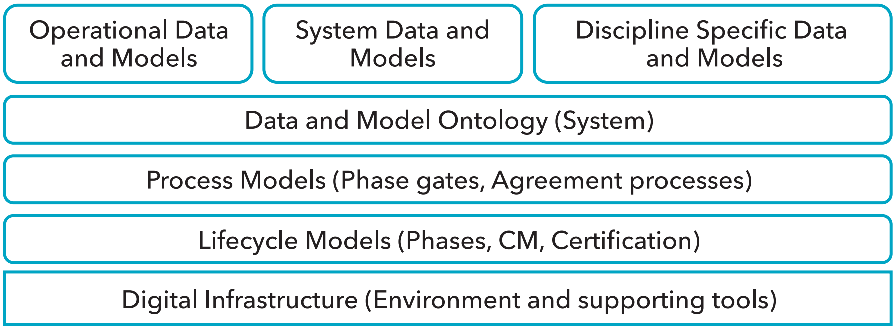


Figure 3. DE/MBSSE measurement framework

also the digital data and models that define and then support the product over its life cycle. Because DE and MBSSE processes help to define the capabilities of the eventual system, the measures can serve as useful leading indicators for other product related measures. DE/MBSSE can also produce independent products in support of delivered data, hardware, and software products such as digital twins or other model- or simulation-based executable systems. For DE/MBSSE, stakeholder concerns include actual users of the systems and software, as well as the development teams, support teams, customer, and enterprise managers. Decomposition of the DE process flow associates with models and underlying data, and the digital infrastructure supporting them.

Figure 3 describes the measurement framework. Data and models are the core products undergoing measurement. These require a system data and modeling ontology to be created, used, and maintained in the ASOT. Process models and associated system life cycle models describe the work process flow, which can also be measured. The digital infrastructure provides the underlying methods and tools for performing the work.

Operational, System, and Discipline Specific Models: DE and MBSSE are primarily concerned with the development and support of models and the data used by the models to support life cycle decisions. There is not a single model, but a set of models used to define the operational use of the system, analyze discipline specific concerns, and manage the relationships between individual models. In MBSSE, the System Model is the result of a unique work activity used as the central repository for design decisions that span multiple engineering and business concerns; design decisions are captured as model elements in that System Model (Delligati 2013).

Data and Model Ontology: Engineers maintain DE and MBSSE artifacts in a repository, referred to as the ASOT, and stakeholders work from the same data and models. For work to proceed efficiently, all users of the repository must be able to work from a common taxonomy and underlying set of ontological relationships maintained by the DE toolsets. User experience is an important measurement attribute.

Process Models: Engineers plan and implement work through a set of defined processes that evolve and produce a set of life cycle artifacts in digital form designed to integrate across the products, people, and processes involved in the project.

Life-cycle Models: DE and MBSSE metrics associate with life cycle phases, decision points, and information needs. These are in turn linked to internal product iterations and external releases. A primary goal of DE/MBSSE is to measure the systems engineering process and product attributes as they progress through these phases.

Digital Infrastructure: The infrastructure includes the establishment of a set of computing assets and tools that support the other DE work in an efficient and productive manner, as well as the training and organizational capabilities to support this infrastructure. Because of the size and complexity of many digital models, the performance of the digital infrastructure is a measurement concern.

DE and MBSSE measurement information model: The benefits of DE and MBSSE are associated with intangible products, defined in software, even though much of the purpose of DE/MBSSE is to improve tangible products. Thus, measurement of DE and MBSSE is primarily a software measurement activity. Because of this, the authors selected the Practical Software and Systems Measurement (PSM) framework as a baseline measurement specification approach. This supported transition of previous research on DE/ MBSSE benefits into specifiable measurement constructs and approaches. PSM defines an information-driven measurement process focused on the technical and business goals of any organization, and allows specification of measurement goals, information, and indicators (Jones, et al. 2001). In addition, the PSM initiative (www.psmsc.com) provides a foundation for publication, training, and support of this work. In this research, the eight primary benefits were translated into measurement specifications using the PSM methodology. This is a community effort sponsored by the SERC, the Aerospace Industries Association (AIA), the International Council on Systems Engineering (INCOSE), the National Defense Industrial Association (NDIA), and PSM. Direct transition of this research informed the development of a draft *DE Measurement Framework and Specification* which was released for comment in January 2022 on the PSM website.

The original PSM guide published in 2001. In 2020, an extension to the guidance published covering additional measurement concepts associated with software and system continuous iterative development (CID). The CID framework directly applies to DE and MBSSE in *the use of evolving models as the primary source of knowledge about a system and its life cycle*. The DE measurement framework further extends the PSM base framework to cover DE/MBSSE measurement concepts.

The PSM methodology encourages development of a measurement information model using Information needs, measurable Concepts, and Measurement constructs. The authors capture these constructs in an "ICM" table. The authors used the causal model to target the ICM table to measures that were specific to DE/MBSSE. The final ICM table will publish with the framework document. The integration of the causal model and the SME-generated ICM table supported the definition of both direct measures of the primary benefits listed in Table 1, as well as the secondary measures of the secondary benefits in the causal model in Figure 2. These come together as the initial measurement framework and measurement model shown in Table 2 on the next page.

A brief description of the measures follows:

- **Product automation**: automated generation of artifacts, including model test activities; digitalization should reduce manual steps in DE processes; programs should measure elimination of manual steps in processes
- **Deployment lead time**: DE and MBSSE should reduce the amount of time from when a capability team identifies a capability to when it is delivered; overall process time and critical steps should be measured
- **Model traceability**: modeling tools support analyses related to the relationships between model elements in a model, such as errors or missing elements, leading to increased completeness and quality

Table 2. Primary Benefits, Direct and Secondary Measures

Primary Benefits	Direct Measure	Example Secondary Measures
Higher level support for automation	Product Automation	Deployment Lead Time, Efficiency, Effort, Cost
Early V&V	Model Review Item Discrepancies	Defect Resolution, Rework, Deployment Lead Time
Strengthened Testing	Defect Detection, Defect Resolution (by phase)	Rework, Deployment Lead Time
Better Accessibility of Information (ASOT)	ASOT Frequency of Access	Deployment Lead Time, Runtime Performance, Number of Consumers of the ASOT
Increased Traceability	Model Traceability	Functional Architecture Completeness and Volatility, Functional Correctness, Product Size and Stability
Multiple Model Viewpoints	Number of Model Views/Artifacts	Efficiency, Runtime Performance, Model Review Item Discrepancies
Reusability	Model Reuse	Automation, Model Traceability
Higher Level of Support for Integration	Deployment Lead Time	Functional Correctness, Efficiency

- **Product size and stability**: modeling tools support analyses related to the number of relevant model elements in a model, supporting comparative analysis of complexity and effort as well as progress to completion of the modeling effort
- **Functional architecture completeness and correctness**: analyses related to the consistency and correctness of the system definition and related artifacts as captured digitally in data and models; may also support analysis of the fidelity of the system description
- **Defect detection and resolution by phase**: detection and resolution of errors and defects by development and product release phase, DE/MBSSE should improve early detection of defects and reduce overall defects in deployed system releases
- **Efficiency**: benchmark measures of process workflows integrating other measures such as effort, lead time, automation, and more
- **Rework**: measures (effort, time, and cost) associated with redoing tasks and products; DE and MBSSE should reduce rework via the knowledge capture inherent in data and models
- **Runtime performance**: amount of time to execute model-related activities, necessary to measure due to the size and complexity of many models
- **Model reuse**: measures such as reduced time and effort arising from different forms of model reuse, such as standard reference architectures
- **ASOT access**: a series of measures associated with different stakeholders and disciplines accessing and updating data and models in the ASOT; a leading indicator of collaboration around models
- **Model view artifacts and review items**: a primary aspect of DE and MBSSE is to improve the development quality and lead time of complex systems via creation, review, and use of models; the effectiveness of those reviews is a key leading performance indicator

DE and MBSSE support systems engineering: The focus on data and models as a foundation to deployed products and services, and the means to instrument and measure the workflow, provide an opportunity to strengthen the systems engineering process. The Systems Engineering Leading Indicators (SELI) Guide, published by INCOSE, identified a set of measures to assess the effectiveness of the systems engineering process (INCOSE 2010). Despite the maturity of these indicators, few complete examples of actual measurement exist, primarily due to the lack of tools that can quantitatively track these measures. With DE and MBSSE, much of the systems engineering process moves from standalone documents to integrated software tools. The causal model and related measures offer the opportunity to define a digital infrastructure to quantitatively measure the effectiveness of systems engineering. Important quantitative measures supporting selected leading indicators from the SELI guide include:

- **Requirements Trends:** Model Traceability, Functional Architecture Completeness, and Volatility
- **System Definition Change Backlog Trends:** Rework, Effort, Efficiency
- **Interface Trends:** Model Traceability, Functional Architecture Completeness and Volatility
- **Requirements Verification & Validation Trends:** Deployment Lead Time, Efficiency
- **Work Product Approval Trends:** Number of Model Views/Artifacts, Deployment Lead Time
- **Review Action Closure Trends:** Model Review Item Discrepancies
- **Defect and Error Trends:** Defect Detection, Defect Resolution, Rework
- **Technical Measurement Trends:** ASOT Frequency of Access
- **Architecture Trends:** Functional Architecture Completeness and Volatility, Functional Correctness, Product Size
- **Cost and Schedule Pressure:** Efficiency, Rework, Deployment Lead Time

Validation of DE and MBSSE measures: At this point there are very few developmental and sustainment programs that are implementing a DE/MBSSE formal measurement program, and fewer that are publishing results to the community on their measurement results. Most of the benefits of DE/MBSSE remain perceived not measured, and the Working Group's efforts to define measurement specifications remain a consensus view of "where do I start" not yet "what are the most valuable."

One publicly reported effort to quantitatively measure the benefits of DE and MBSSE comes from the U.S. Navy Submarine Warfare Federated Tactical Systems (SWFTS) program, published in 2021 (Rogers and Mitchell 2021). The SWFTS program has been transitioning from a document-centric systems engineering process to a model-based process over the past decade. The publication quantified a positive return on investment from this transition based on several quantitative measurement activities. The authors make several conclusions about DE/MBSSE based on the metrics they took/calculated. First, the MBSSE process was more *efficient* than the legacy process, specifically about the *effort* needed to modify and configuration-manage interface requirements. Second, MBSSE enabled interface *defects* discovery earlier when it is typically less expensive to fix. Third, MBSSE produced a higher quality product, in terms of total number of *defects* found. Finally, the authors determined that a positive project *cost* ROI was achieved from the investment to use MBSE, as compared to previous product releases. The authors also note additional qualitative and observed benefits throughout. Since moving to the MBSSE process, the paper reported a 37% decrease in fielded product trouble reports, a 9% decrease in overall problem reports, an 18% increase in "saves" or problems discovered in earlier phases, and an 18% decrease in total systems engineering effort hours.

SWFTS quantified these primary benefits: Increased Traceability, Early V&V and Strengthened Testing, Support for Integration, and Automation. The work demonstrated measurement approaches related to Product Automation, Efficiency, Model Traceability, Functional Completeness, Functional Correctness, Defect Detection and Defect Resolution, Product Size (of baseline changes), and Effort. The program coupled these measures to the organizations financial (effort, cost, and schedule) tracking systems to establish the comparative benefits. A primary aspect of this work is its consistency with the causal model and related measures and measurement framework.

In discussions with other programs that are developing a DE/MBSSE measurement approach, the link from DE/MBSSE benefits to fielded product timeliness, quality, and effort remain strong. The focus on product quality, as measured in defects per phase and elimination of rework, stays front and center. One program was primarily interested in the ability of a DE/MBSSE process to improve both cycle times of internal and deployed releases, as well as cycle time consistency.

However, most organizations and programs surveyed to date are just beginning to define a DE/MBSSE measurement activity. These are helping to define the core measures as reflected in the DE Measurement Framework but not at the point where full validation of the causal model is possible. The community needs continuing efforts to mature the practice of DE/MBSSE measurement.

Maturing DE/MBSSE measures: In summary, the community is gaining a much greater understanding of the opportunity to quantify DE/MBSSE measures, but actual implementation, lessons learned, and experience remain in preliminary stages of practice. The DE/MBSSE community continues to search for a starting point for measures. This research to categorize MBSSE benefits and the resultant causal model, as well as the first draft DE measurement framework, will provide a baseline for programs to begin focused efforts on measurement and quantification of benefits. The digital transformation and shift from document-based to model-based artifacts offer a wonderful opportunity to quantify and expand the application of systems engineering to complex projects.

DE/MBSSE tools support the quantitative data needed to collect and analyze these measures. For example, a core focus of current MBSE tools is traceability, and most offer the means to measure Model Traceability directly. From this, the community can derive Functional Completeness and Volatility as well as Functional Correctness. Also, modeling tools all define model elements which can be directly converted to Product Size, although the definition of elements varies from tool to tool, and additional experience is needed on the most valuable model element relationships to measure. Most of the MBSSE tools surveyed provide configuration management support but do not directly support quality measures such as Defect Resolution and Rework. However, programs can today build the digital infrastructure to support tracking of these measures through tool integration standards and features.

As the maturity of DE/MBSSE measurement practice increases, this initial baseline measurement framework and underlying causal measurement model will continue to inform the community. ■

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Systems Modeling Language (SysML v2) Support for Digital Engineering

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ABSTRACT
The OMG Systems Modeling Language™ (SysML®) was adopted in 2006 and has been used by many organizations to support their efforts to transition to a model-based systems engineering (MBSE) approach. SysML v2 is the next generation Systems Modeling Language and is intended to address many of the limitations of SysML v1. This paper highlights how the SysML v2 language and the new standard Application Programming Interface (API) can enable MBSE and digital engineering.

SysML v2 is being developed by the SysML v2 Submission Team (SST) in response to requirements issued by the Object Management Group (OMG). The final submission to the OMG is planned for 2022. The draft SysML v2 specifications and the open-source SysML v2 pilot implementation can be found at https://github.com/Systems-Modeling.

KEYWORDS: SysML v2, SysML v2 language, SysML v2 API and services, digital engineering, digital thread

INTRODUCTION

Digital Engineering is an engineering approach where the artifacts of the engineering processes are captured digitally and semantically integrated. In other words, the engineering artifacts that compose the technical data package, including specifications, design, analysis, and verification data, are an integrated data set that can be interpreted by both people and computers. In doing so, computers can be leveraged to enable automation, and to improve the efficiency and quality of various tasks, such as querying, analyzing, validating, and exchanging the data.

MBSE is the application of systems engineering where a primary artifact of the systems engineering process is a model of the system, often referred to as the system model. This contrasts with more traditional systems engineering approaches where information about the system is captured in various kinds of document-based artifacts including text, spreadsheets, and informal drawings. Both MBSE and traditional systems engineering approaches often include various analytical models that describe different aspects of the system, such as its performance, reliability, and mass properties. A system model can facilitate the integration of these different aspects by using a common representation of the system.

SysML v2 includes a modeling language and an API. The SysML v2 modeling language enables the expression of the core concepts needed to precisely represent the system, its elements, and its environment. In addition, the API provides a standard set of services to interact with SysML v2 models that can now be managed, scaled, and connected with other product information in the context of Digital Engineering. This facilitates interoperability between the system modeling tools that are used to create the system model, and other engineering tools that either provide or consume data about the system. For example, an analytic modeling tool, such as a performance analysis tool, may use the API to query the system model to obtain key system properties that are required to perform the analysis.

There is a clear relationship between SysML v2, MBSE, and Digital Engineering as indicated in Figure 1. SysML v2 provides the capability to represent the system model. The system model is a primary artifact of an MBSE approach. This model provides a common representation of the system that can be used to integrate other engineering artifacts, including electrical, mechanical, software, analysis, test, and manufacturing artifacts. Thus, the system model that is created using SysML v2, and the API that facilitates access to this model, can be a foundation for Digital Engineering. SysML v1 provides an initial capability to facilitate this integration. However, SysML v2 provides a significantly enhanced capability which is explained below.

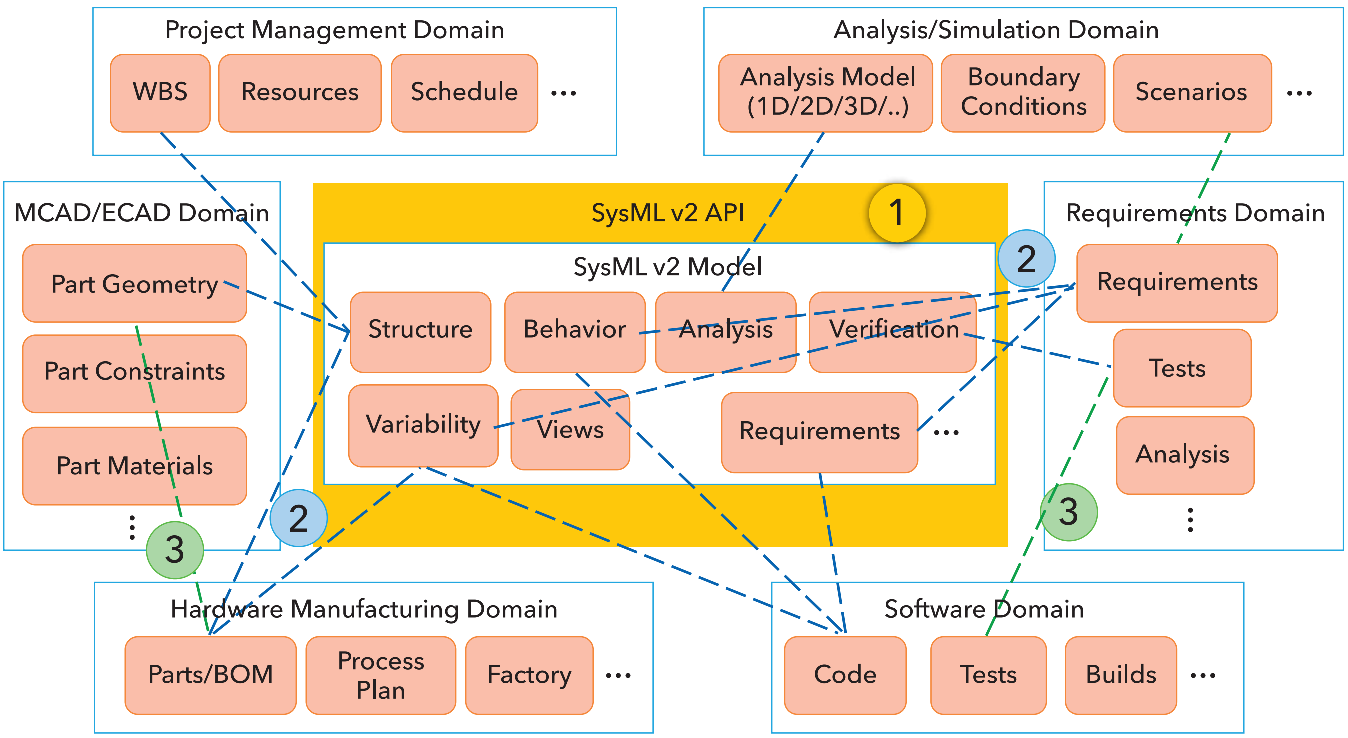

Figure 1. SysML v2 enables integration of engineering artifacts in support of Digital Engineering

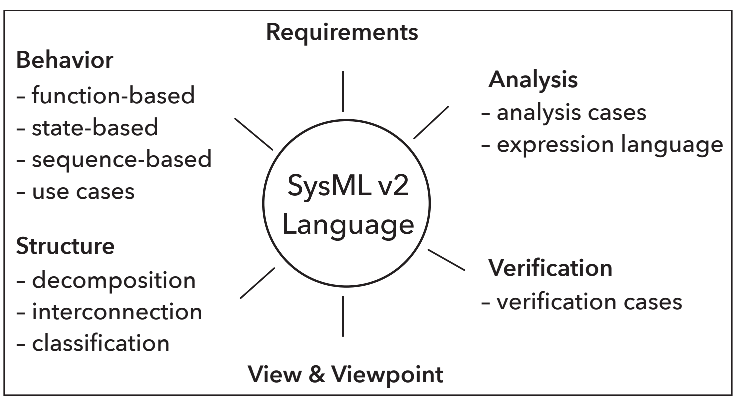

Figure 2. SysML v2 language functionality

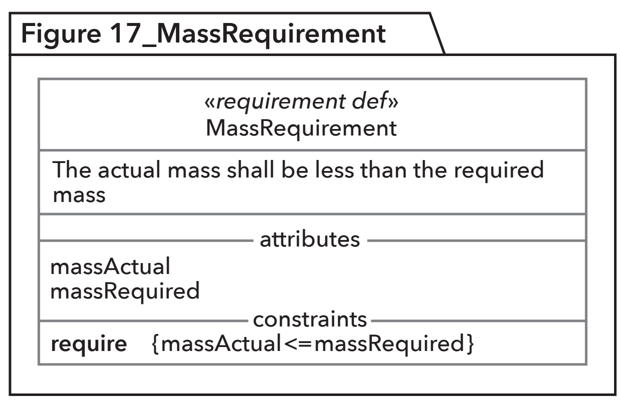

Figure 3. Mass requirement

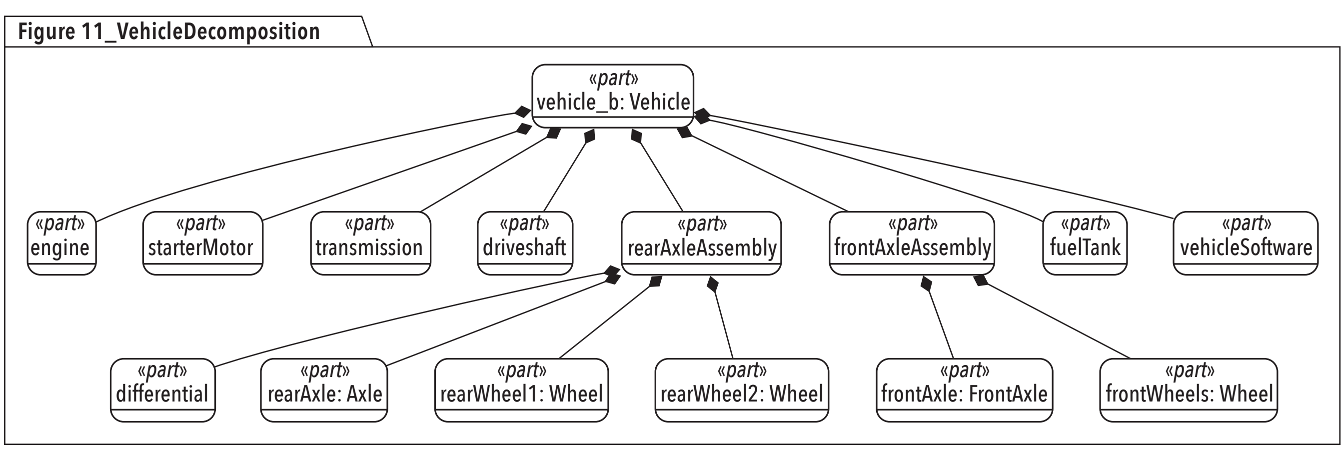

Figure 4. Vehicle parts tree

SYSML V2 LANGUAGE HIGHLIGHTS

SysML v2 improves the precision, expressiveness, consistency, and integration of the language, and improves overall interoperability, compared to SysML v1. This in turn results in a more robust system model, and improved integration between the system model and other engineering artifacts.

SysML v2 expresses the core concepts required to represent the system as highlighted in Figure 2. Annex B of the SysML v2 specification includes an example vehicle model that demonstrates how these concepts can be used to model a system. The following is a preview of the vehicle example from Annex B.

Requirements. The requirements of the system are constraints that a valid system design must satisfy. A constraint is a Boolean expression that can be evaluated as true or false. Figure 3 shows an example mass requirement. The text statement of the requirement is augmented by the Boolean expression {massActual<=massRequired}. A user can obtain the massActual by a mass rollup analysis or by measurement and compare the massActual to the massRequired to determine whether the vehicle design satisfies its mass requirement.

Structure. The structure of the system describes the system and its constituent parts at any level of nesting, as shown in the vehicle parts tree in Figure 4. The structure can also describe how these parts interconnect via their ports as shown in the vehicle parts interconnection in Figure 5.

Behavior. The behavior of the system can describe how the system changes over time in response to different kinds of stimulus. Figure 6 shows a simple state-based behavior of the vehicle. The vehicle has two nested concurrent states called operatingStates and healthStates. In the operatingStates, the vehicle transitions from the off state to the starting state to the on state. When the vehicle is in the on state, it performs the provide power action (not shown), where it provides power to its wheels. Figure 7 depicts the action flow for provide power.

SYSML V2 API HIGHLIGHTS

The SysML v2 API provides standard services to operate on SysML v2 models, such as to navigate and query the model, to create and update model elements, to establish versions of the model to support configuration management, and to manage relationships with external data. A SysML v2 API provider tool provides the standard services that are consumed by a SysML v2 API consumer tool. Consumer tools can interact with the provider tools using

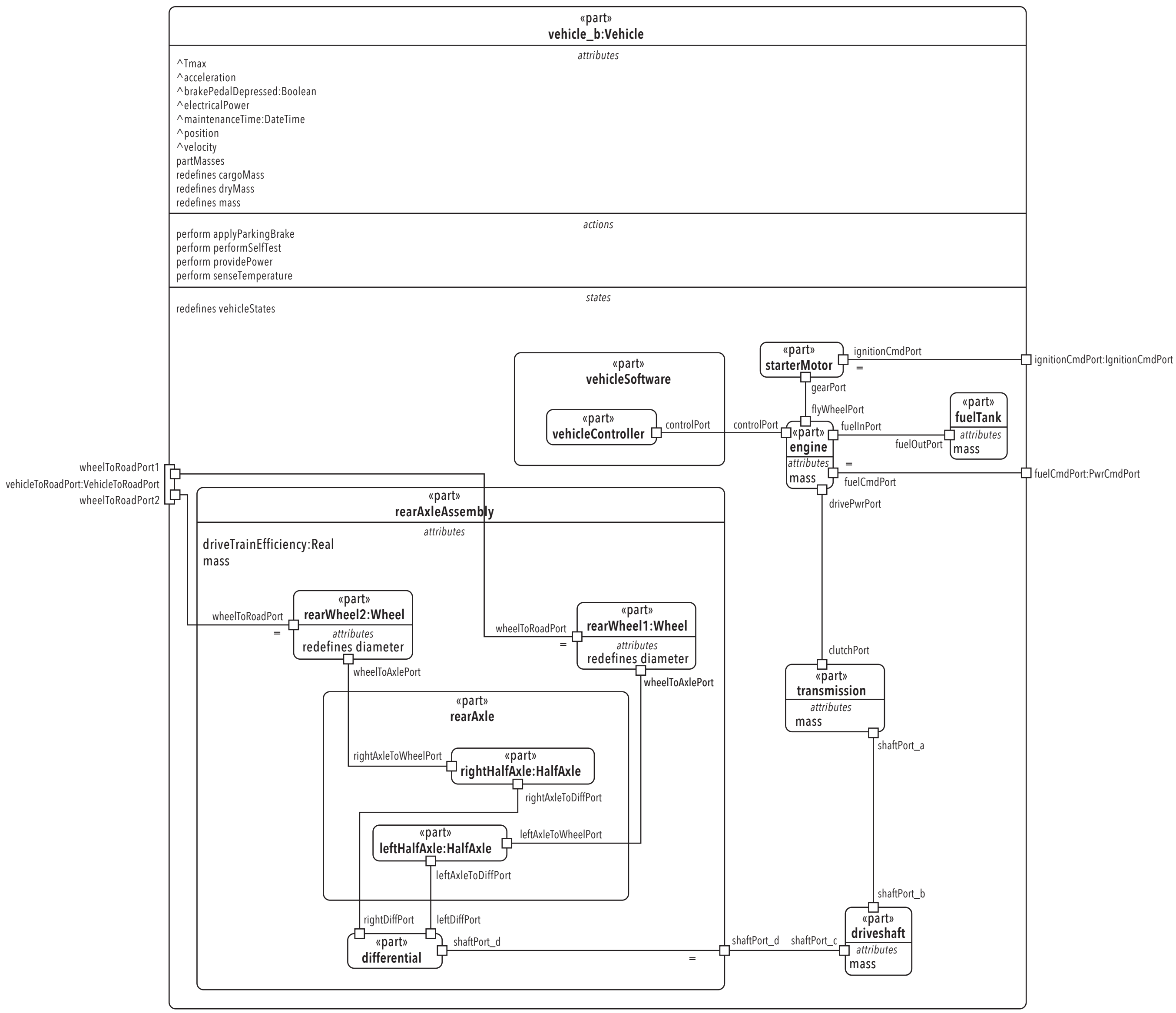

Figure 5. Vehicle parts interconnection

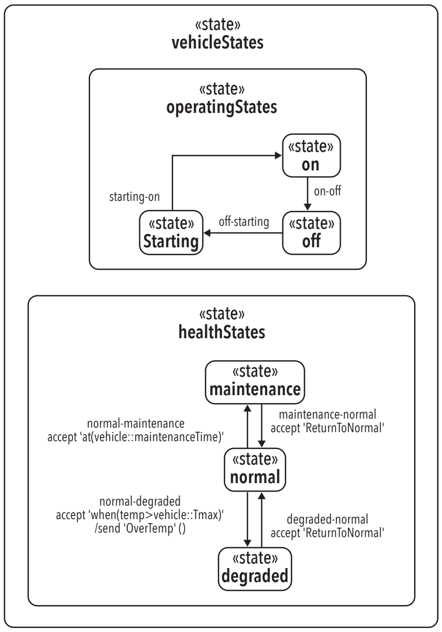

Figure 6. Vehicle states

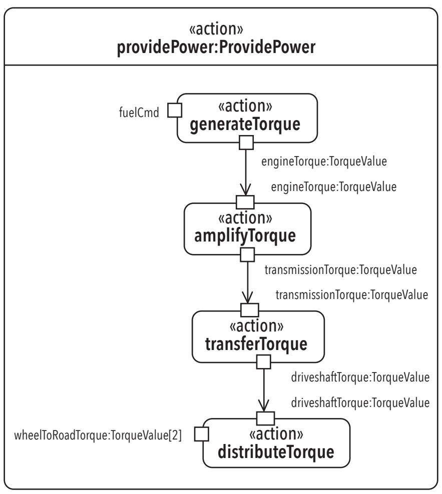

Figure 7. Provide Power action flow

the standard API, agnostic of the backend technology stack of the provider tools.

The SysML v2 API specification includes a Platform Independent Model (PIM) and two Platform Specific Models (PSMs). Figure 8 illustrates the role of PIM and PSMs in the pilot implementation of SysML v2 API and Services. The PIM serves as the logical API model and provides a specification of services independent of the platform or technology. This includes the definitions of all services, the operations included in each service, and the data model for the inputs and outputs of the operations. The PSMs are bindings of the PIM using a particular platform/technology, such as REST/HTTP, OSLC, Java, and .NET. Multiple PSMs can exist for a given PIM. The first version of SysML v2 API specification will include a REST/HTTP PSM and an OSLC 3.0 PSM, and the mapping from PIM to both the PSMs. A SysML v2 provider tool will typically provide services conformant to either or both PSMs. The choice of REST/HTTP PSM is key. Most modern programming languages provide libraries for consuming REST/HTTP APIs. Enterprise applications, written in any modern programming language, can consume the standard SysML v2 API, and interoperate with multiple API providers.

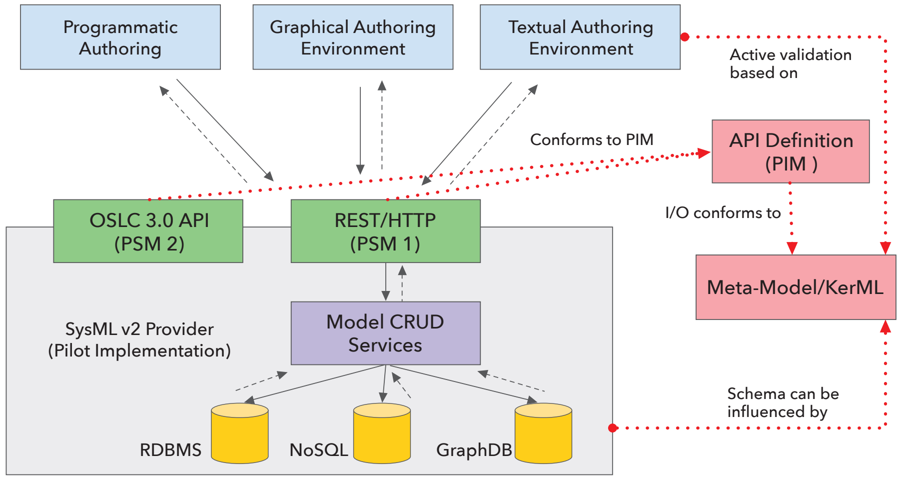

Figure 8. Use of PIM and PSM to specify SysML v2 API and Services

As noted previously, the API enables interoperability between the SysML v2 model and other engineering artifacts and provides the capability for creating and managing digital threads. An example digital thread built with SysML v2 models using the Syndeia Digital Thread Platform is shown in Figure 9. SysML v2 model elements and relationships are accessed using the standard REST/HTTP API. As shown using the color key, the purple-colored nodes are originating from a SysML v2 model. The figure shows the vehicle mass requirement (vehicleMass1) associated with the vehicle part definition (vehicle) in a SysML v2 model. The Verify vehicle mass test case, defined in Zephyr Scale/Jira test management system, is used to verify the vehicle mass requirement. The verification task and its detailed steps are defined in Jira (blue node SDB-2251) and is associated to the verification software managed in a GitHub branch (gray node feature/vm). The detailed results and reports of the verification process (green node Mass implementation results) are managed in Artifactory. The vehicle part definition in the SysML v2 model is also linked to the vehicle assembly in the Aras PLM system (red nodes).

COMPARING SYSML V2 WITH SYSML V1

Metamodel. SysML v1 is an extension of the UML metamodel. SysML v2 is based on a new metamodel that is grounded in core declarative semantics based on formal logic. The semantic grounding significantly increases the precision of SysML v2 and facilitates semantic integration with other engineering data.

API. SysML v1 does not provide a standard API. Consumer tools navigate, query, create/update SysML v1 models using the programming language-specific APIs offered by the provider tools (aka UML/SysML modeling tools). SysML v2 provides a standard API with REST/HTTP and OSLC 3.0 bindings that will make it possible for consumer tools (business/engineering applications) to: (1) interact with SysML v2 models using any modern programming language, and (2) interoperate with multiple provider tools.

Graphical and textual notation. SysML v1 includes a graphical notation. In addition to the graphical notation, SysML v2 also includes a textual notation. Figure 10 is an example that shows the textual notation for the vehicle parts tree shown graphically in Figure 4. The graphical and textual notation are different renderings of the same underlying model. A tool should enable a modeler to create the model using the graphical and textual syntax in tandem. For example, any part of the model can be created in text, and then viewed graphically, or vice versa. The combination of a graphical and textual syntax improves the ability to graphically represent architectural views of the model, while at the same time, providing a compact textual representation of more detailed parts of the model that can include formal expressions.

Reuse pattern. SysML v1 includes the ability to define an element, such as a block, and then reuse it in different contexts. SysML v2 applies this reuse pattern consistently across the entire language. The pattern can be applied to parts, actions,

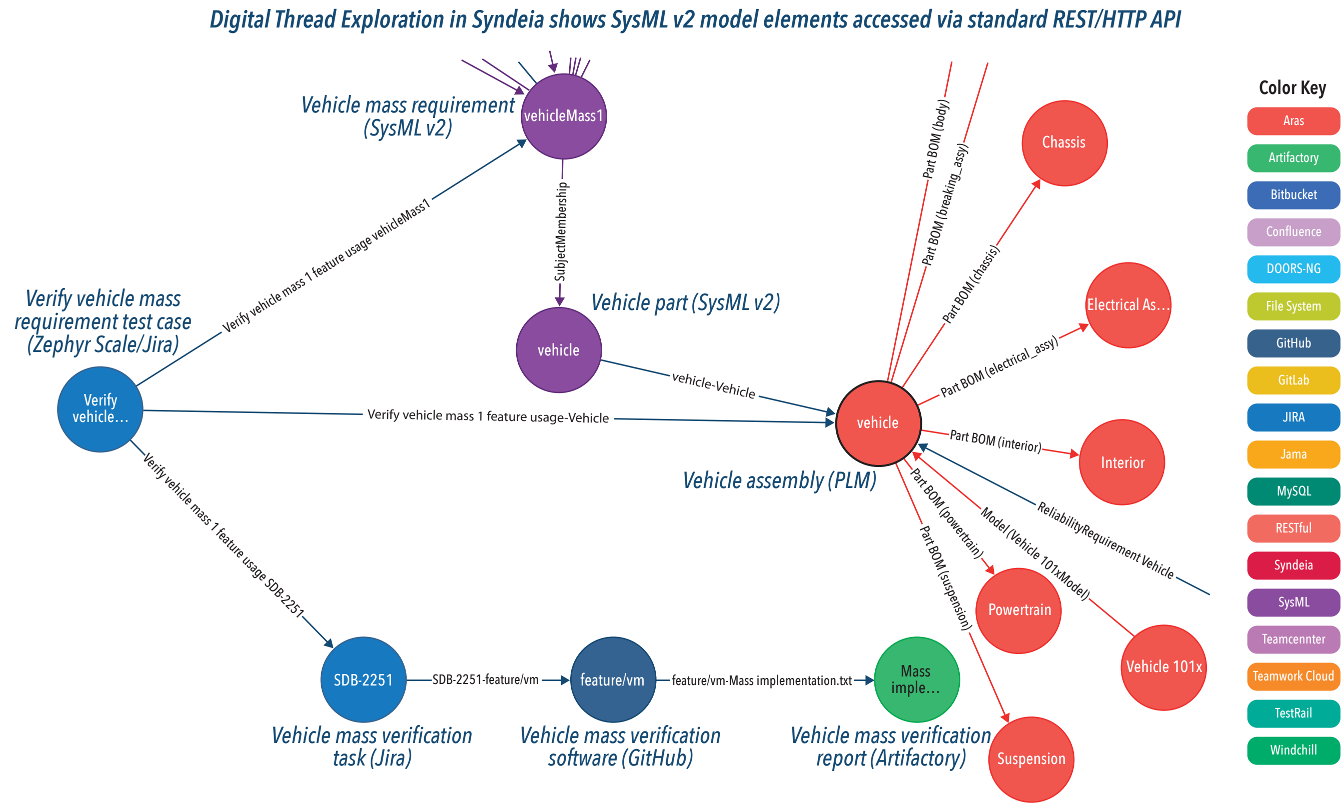

Figure 9. SysML v2 model elements as part of a Digital Thread - view in Syndeia Digital Thread Explorer, Bajaj and Sharma (2021)

requirements, and any other kind of model element. This pattern, coupled with fundamental variability concepts in SysML v2, facilitates model reuse at any level of design (such as a system, component, or feature), and the ability to maintain multiple variant design configurations.

Interoperability. SysML v1 relies on the XML Metadate Interchange (XMI) standard as the basis for model interchange. The XMI format is difficult for tool vendors to exchange, particularly for large and distributed models. The SysML v2 textual notation provides a natural means for file exchange. In addition, the standard API supports the dynamic exchange of SysML v2 model data both via a repository or via files, using a common data representation. Some example scenarios that the API can support include requirements change impact assessment, querying the traceability of system model elements in a digital thread, and executing an analysis. The improved model interchange and API will enable SysML v2 to provide more robust interoperability with other engineering models and tools.

SUMMARY

SysML v2 provides an improved ability to represent an integrated model of the system that can evolve throughout the system life cycle. As such, it can provide a persistent framework for integrating other discipline-specific models of the system. It is considerably more precise, expressive, and interoperable than SysML v1. These improvements are critical to enabling Digital Engineering and the semantic integration of digital artifacts that compose the technical data package. ■

```
package vehiclePartsTree{
    part vehicle_b:vehicle {
        part engine;
        part starterMotor;
        part transmission;
        part driveshaft;
        part rearAxleAssembly;
            part differential;
            part rearAxle:Axle;
            part rearwheel1wheel;
            part rearwheel2:wheel;
        }
        part frontAxleAssembly{
            part frontAxle:FrontAxle;
            part frontwheels:wheel[2];
        }
        part fuelTank;
        part vehicleSoftware;
    }
```

Figure 10. SysML v2 model in textual syntax, shown in Jupyter notebook

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- SysML v2 pilot implementation and release repository, available at: https://github.com/Systems-Modeling

ABOUT THE AUTHORS

Manas Bajaj, PhD is the Co-Founder and Chief Systems Officer at Intercax. Dr. Bajaj leads Intercax's product research and development, including the flagship Syndeia platform for enabling Digital Threads for model-based engineering of complex systems. He was a contributor to the SysML (Systems Modeling Language) 1.0 open standard and leads the SysML v2 API and Services standards development as part of the SysML v2 Submission Team (SST). He has served as a Principal Investigator (PI) on multiple small business innovation research (SBIR) grants with NASA and NIST, and has over 20 years of experience in modeling, simulation, software architecture and development, and working with multiple industry verticals, such as aerospace, defense, automotive, transportation, and electronics. His research interests are in the areas of Digital Thread, MBSE, MBE, product lifecycle management (PLM), application lifecycle management (ALM), computer-aided design (CAD)/computer-aided engineering (CAE), Open Data and API initiatives, and artificial intelligence/machine learning (AI/ML). He is an author of the OMG Systems Modeling Certification) Preparation (OCSMP) certification program.

Sanford Friedenthal is an industry leader and independent consultant in MBSE. He has over 30 years of experience as a system engineering practitioner, department manager, and as a leader of organizational initiatives for Lockheed Martin. Mr. Friedenthal also has been a leader of the industry standards effort through the OMG and INCOSE to develop the SysML® that OMG adopted in 2006. He is co-author of "A Practical Guide to SysML" and "Architecting Spacecraft with SysML" and is now co-lead up of the SysML v2 Submission team to develop the next generation of SysML v2.

Ed Seidewitz is Chief Technology Officer at Model Driven Solutions, Inc., a long-time provider of enterprise and systems architecture services using model-based methods. Mr. Seidewitz has over 30 years of professional experience with the modeling, architecture, and development of systems spanning diverse domains including aerospace, finance, acquisition, and healthcare. Mr. Seidewitz has been active with the OMG for 20 years, including involvement in every UML Revision Task Force and with the Service Oriented Architecture Modeling Language (SoaML) and SysML specifications. He was primary author of the Foundational Subset for Executable UML Models (fUML) and Action Language for Foundational UML (Alf) specifications and maintains open-source reference implementations for both. He is currently chair of the OMG Model Interchange Special Interest Group and of Revision Task Forces for fUML, Alf, Precise Semantics of UML Composite Structures and Precise Semantics of State Machines. He is also co-leader of the SysML v2 Submission Team and leader of the Precise Semantics of Time for fUML Submission Team.

Being Digital: Why Addressing Culture and Creating a Digital Mindset are Critical to Successful Transformation

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ABSTRACT

Technology continues to drive nearly every aspect of our daily lives – both personal and professional. As organizations race, and sometimes fail, to adopt digital change, we must continually ask ourselves what drives a successful digital transformation?

We believe that true transformational change can only be achieved when technology & culture are in lockstep, creating the necessary Digital Mindset to not only deploy the correct solutions, but the right organizational culture is in place to adopt and accelerate the technical change. Being Digital is about more than the technology an organization deploys; it is about the very fabric of that organization's character — their Digital DNA.

Only when we fully cultivate the right mindset can we set the conditions for the right culture to flourish and ascend from merely doing digital things to truly Being Digital.

THE DRIVE TO DIGITAL

Digital defined and will continue to define the 21st century. At every turn, an increasingly digital world confronts us. Our entertainment, our shopping, our social lives, our jobs – all of these get directly impacted by the digital experience. As technology continues to press the boundaries of what is possible – in physical devices and virtual capabilities – the pace of change continues to escalate.

Given these factors, it is not surprising that all kinds of organizations continue to strive to harness the power of the digital revolution to drive their strategic objectives, be they commercial businesses, non-profit organizations, or federal, or local governments. Everywhere we turn, organizations are trying to *Be Digital.*

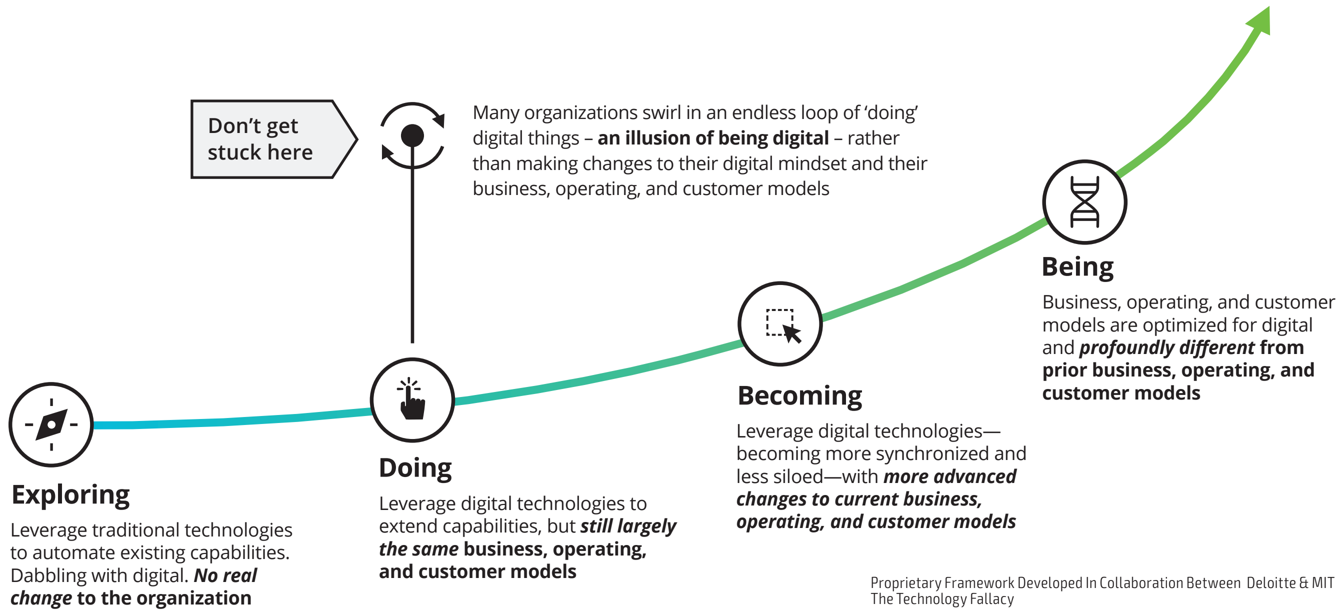
FROM *EXPLORING* TO *BECOMING* A DIGITAL ORGANIZATION

But what does that mean? Our experience in multiple industries across multiple clients shows us again and again, that while organizations will almost unanimously say that they want to *Be Digital*, very few have a clear understanding of what that means or how to fully achieve it. What we commonly see is progression along this basic maturity curve.

It begins with an understanding that, to remain successful and competitive, an organization must embrace digital principles. Leaders and staff begin to speak the words of 'digital change' or 'digital transformation' without even fully understanding what it is or how to achieve it – but the **Exploring** begins. Organizations then quickly progress towards **Doing** digital things – they purchase new technology platforms, begin to leverage new tools, and deploy new solutions. But in many organizations, the change is only at the surface level. The same processes, behaviors, and operating models are in place, they just now have a new wrapper placed around them. Ways of working, governance models, talent models, policies – all the legacy components of the pre-digital era are in place. In these cases, the organization merely upgraded to a newer version of its older self; there is no fundamental change. This is a trap we see again and again with organizations all over the world: **They Do Digital Things, But Never Actually Become a Digital Organization**.

WHAT IT MEANS TO *BE DIGITAL*

So how do organizations successfully navigate out of this cycle and truly become digital? It begins with addressing the



Proprietary Framework Developed In Collaboration Between Deloitte & MIT
The Technology Fallacy

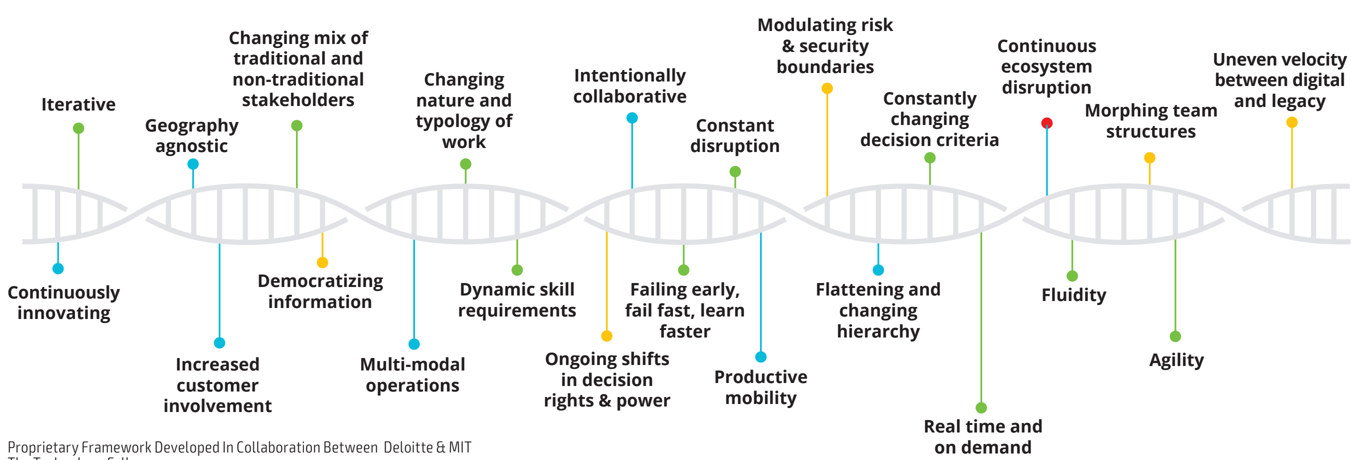
underlying components that truly make a digital organization. In the 2019 book The Technology Fallacy, Deloitte thought leaders and MIT researchers delved into this question and developed the concept of Digital DNA – those innate traits, deep within an organization's core values and operations – that truly make an organization digital.

Surprisingly, none of these traits are inherently technological. While successfully implementing technology solutions can accelerate and enable these traits, things like democratizing information and flattening decision hierarchies say more about the people, process, behaviors, and values of an organization than their software, data, or devices. Organizations can build a knowledge management platform, but if people still retain centralized control of information and data, then that information can never be truly shared and democratized. Managers can talk about enabling and empowering localized decision making, but many line managers still feel the need to seek approval and direction before acting

This is where the fundamental truth of true digital transformation is revealed – **any successful digital transformation effort must address not only an organization's Digital Technology, but more importantly, enable the right Digital Mindset and Culture**.

ADOPTING A DIGITAL MINDSET AND CHANGING ORGANIZATIONAL CULTURE

Changing culture requires changing the narrative in our offices and boardrooms and water coolers from 'technology version update' to 'a fundamental shift in our organization's operations and behavioral habits." Any transformation effort that does not focus on the necessary cultural and organizational impacts will always be suboptimal and will result in continually spinning in the *Doing Digital* space versus progressing along the maturity curve to truly *Being Digital*. So, what's the answer then? If organizations wish to mature their actual Digital DNA – not just the technology and tools they use to support them – how do they functionally address the underlying issues? How can they treat not only the symptoms, but the underlying root cause as well? It starts with realizing that the culture and mindset of the organization is the key enabler or prohibitor of success. Culture is the unstated "how things work here" mindset for every organization; organizations with a culture that aligns with their digital vision will adapt easily to new operating models, mature quickly, and exploit opportunities for digital success without losing their core values and beliefs. Similarly, organizations whose culture runs counter to the expressed objectives of digital transformation will take much longer, maybe too long, to adapt. It's commonly said that "culture eats strategy for breakfast," and failure to address the underlying culture will simply result in putting a new coat of technological paint over the same crumbling organiza-



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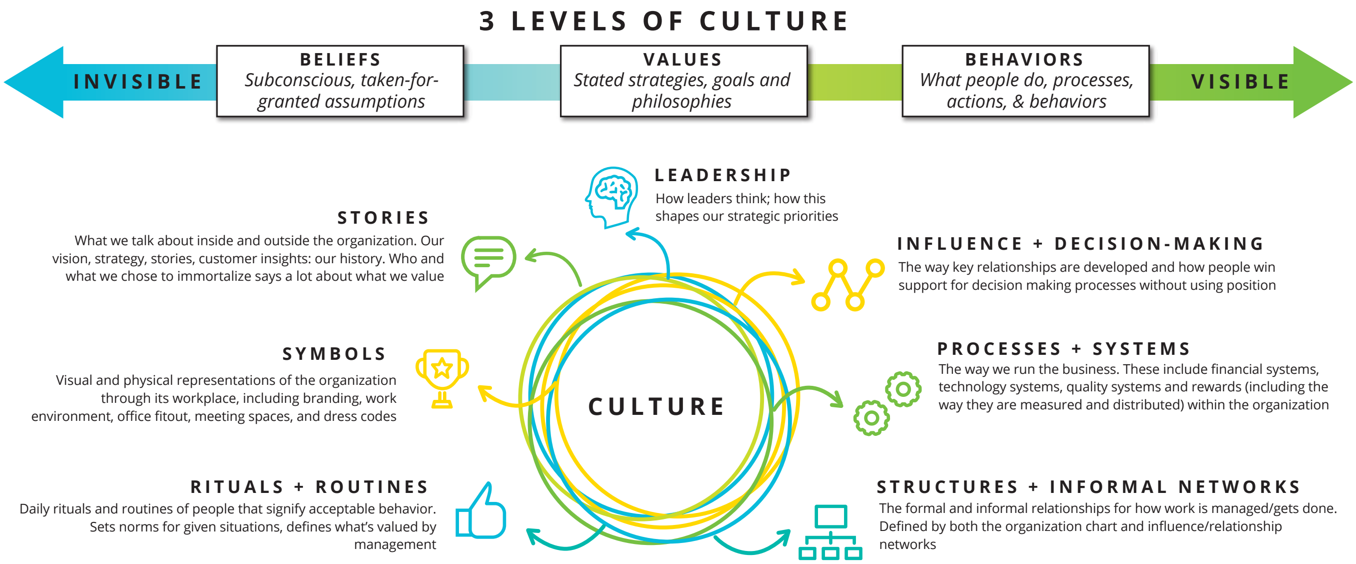


tional walls. It might look better for awhile, but eventually the cracks will show and the unaddressed root causes will prevent an organization from truly *Being Digital*.

Understanding this concept is relatively easy, but implementing it continues to be a challenge for many organizations. To succeed, digital transformation efforts must not only invest in the latest technology solutions, but also focus on driving cultural change. Becoming a truly digital organization requires that **organizations change the way they organize, the way they lead, manage, operate, and – most importantly – how they behave**.

WHAT IS YOUR ORGANIZATION'S CULTURE?

Culture is the strongest enabler or derailer to digital transformation. Without a culture that encourages and rewards the behaviors that organizations seek to achieve, true success will always elude them. Despite their best efforts, people are not always rational actors; even when they know that changing can be good for them – eating better, being more mindful, exercising more, watching less television – they often don't change because engrained behavioral habits trump rational logic.

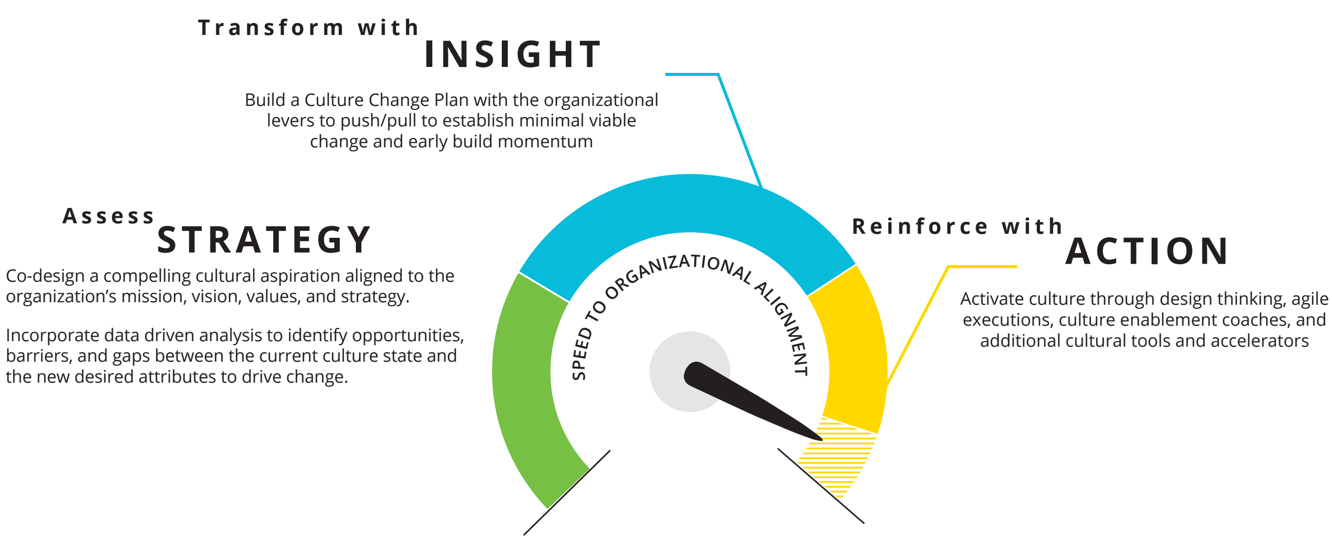
These behaviors are driven by our beliefs and values – not what we find on the corporate mission statement, but the stories, lessons, and trends we see in the workplace. We often define organizational strategy as 'what work needs to happen' and organizational culture as 'the way that work actually gets done' in our respective organizations. The gap between strategy and culture results from multiple factors such as the stories that are told, the symbols that we see, the rituals and routines we exhibit, as well as how our leaders operate, and how our teams are structured and work, and most importantly what is reinforced, recognized, and rewarded in the organization.

Given that some of these factors are nebulous, defining them – let alone trying to change them for the better – can seem almost impossible. How can they change something which can barely be described?

BUILDING THE DIGITAL CULTURE NEED TO SUCCESSFULLY TRANSFORM

Changing and building a Digital Culture can be challenging, especially in highly technical organizations that view digital transformation as simply the acquisition of hardware, software, and tools. As with any plan, the first step is to understand the desired objective – what does a successful future look like and how does the workforce need to behave and work in that future – and then assess your current state in comparison to that desired state. Then identify gaps, plan, and execute initiatives, and monitor measures of effectiveness.

The concepts are simple enough, but culture change cannot be solely led from



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the top-down. Finding influential leaders in junior and mid-level positions is critical. C-Suite leaders need to demonstrate digital leadership, enabling transformation without being seen as directing it. The greatest advocates and enablers (or threats) may be people with very little formal authority in your organization. Nevertheless, these informal leaders serve as the collective memory, conscience, and trendsetters in your organization and must be harnessed.

In conclusion, to BE a Digital Organization, leaders must not solely look to acquire digital technology. They must set a clear vision for how people work, share information, collaborate, make decisions, use their judgment, and stay nimble and agile. Leaders must role model and emphasize those behaviors through stories, while ensuring that their talent life cycle (recruiting, hiring, training, performance management, rewards and recognition, promotion, and more) aligns to reinforce that culture. Also, in many organizations there already exist "pockets of digital excellence" that come closest to embracing what it means to *Be Digital*. Seek to understand the factors that make them successful and help them share their story across the enterprise.

If organizations can do this, they will move from *Doing Digital* to truly *Being a Digital Organization*. ■

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He has provided strategic advice and counsel to clients from across the Government and Commercial Sectors, and his clients include the following Public Sector organizations: UNICEF, American Cancer Society, U.S. Air Force, U.S. Navy, U.S. Army, U.S. Marine Corps, Office of the Secretary of Defense, U.S. Transportation Command, Special Operations Command, U.S. Department of Commerce, U.S. Patent and Trademark Office, U.S. Department of Agriculture, U.S. Forest Service, U.S. Department of Veterans Affairs, U.S. Department of Housing and Urban Development

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He has over a decade of business experience, working in technology and operations consulting. Prior to his consulting career, Jason spent 8 years as an officer in the U.S. Army, commanding & leading organizations of 200+ soldiers. During his career, he has led multiple consulting engagements across the Department of Defense, the Intelligence Community, and other Federal government agencies - developing expertise in digital transformation, organizational assessment and design, culture, change, and communications.

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Constructing an Authoritative Source of Truth in a Changing Information Landscape

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ABSTRACT

In support of the US Army Mission System Architecture Demonstration, Adventium Labs conducted a series of interviews and demonstrations to determine requirements, best practices, and available tool capabilities for building and maintaining an Authoritative Source of Truth (ASoT). An ASoT is a capability that gives definitive answers to queries about a target collection of systems. An ASoT should make information discoverable, enable controlled information sharing, and maintain traceability across time and organizations. The challenges to establishing an ASoT include limited standards adoption by tool vendors, entrenched workflows, and data rights management needs. The systems engineering community can overcome these challenges by keeping ASoT needs at the forefront when planning engineering activities, investing in open and flexible standards for information sharing, and leveraging emerging connectivity tools and model-based systems engineering methods.

KEYWORDS: digital engineering, authoritative source of truth, information management, model-based systems engineering

1.0 INTRODUCTION

US Department of Defense (DoD) procurement authorities are shifting to a paradigm in which there will always be a "credible threat of re-compete," by enabling the acquiring agency to own enough of the system architecture so that they can change vendors without a complete restart. Success depends on describing the system as separable building blocks. Emerging technologies, such as the congressionally mandated Modular Open Systems Approach, the Future Avionics Capability Environment (FACETM) Technical Standard, and Model-Based Systems Engineering (MBSE), provide key support while introducing new challenges. Whereas authorities once accepted only paper documents, they must now accept a variety of machine-generated artifacts. Whereas authorities once worked with a single intellectual property owner, they now must navigate multiple owners and data rights. To meet these challenges, the DoD calls on its programs to establish an Authoritative Source of Truth (ASoT) that will embody core capabilities such as information traceability, access controls, and provenance (DoD Digital Engineering Strategy, p8. See https://www.acq.osd.mil/se/docs/2018-DES.pdf).

Recently the US Army, as part of its Joint Multi-Role Mission Systems Architecture Demonstration *Capstone exercise*, tasked Adventium Labs to elicit, refine, and exercise requirements for an ASoT. The objectives of this study were to (1) define requirements for an ASoT at a sufficient level of detail as to enable its acquisition and use in support of future DoD model-based system developments and (2) provide proof-of-concept demonstrations that the requirements could be satisfied using available technologies. This paper summarizes our results from that study.

The study revealed that the true value of the ASoT lies in its capture of *relationships* between system artifacts. While we may imagine the ASoT to be a *single repository with a single owner* that holds everything that the DoD needs to build the operationally approved system, in reality the ASoT will be a *program-specific collection* of component repositories *under the control of multiple stakeholders* that uses a mix of standardized, custom, and manual interfaces along with stakeholder-specific knowledge and processes, all operating under manual control and oversight, to manage builds of the system. Although we might hope that the contents of the ASoT derive from *discrete, standalone* build processes, those contents will derive from time-sensitive selections from vendor-proprietary product lines, and the DoD must specify in advance the details that it will require to re-compete those contents. The study also revealed that although building an ASoT is technically feasible, much work remains to communicate its proper use among all of the stakeholders.

In Section 2, we briefly recount our investigative process. In Section 3, we summarize our recommendations for procuring and assembling an ASoT. In Section 4, we provide references to additional resources (including the long form report of our study).

2.0 OUR PROCESS

The Capstone exercise focused the method and goals of our investigation. The Capstone exercise brought together major aerospace organizations (*Capstone performers*) to collaborate, develop and exchange models and software, and "put some miles" on the digital engineering tools and standards that have been gaining momentum during the past decade. The performers also received model-based Government Furnished Information (GFI) to inform their designs. In the context of the Capstone exercise, we conducted a broad conceptual exploration via user stories, refined those user stories to requirements with input from our Army customer, and conducted feasibility demonstrations driven by the DoD's prioritization of the requirements.

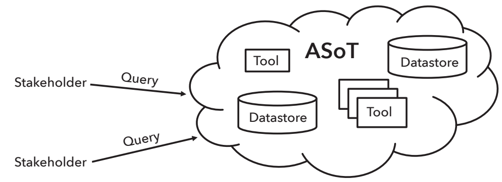

Figure 1: Authoritative Source of Truth in context

Table 1. Descriptions of Critical Priority Requirements Categories with Select Examples

Requirements Category	Description	Example Requirements (with Reference Number)
Access Control (User Story 2702)	The ASoT must restrict access to stakeholder intellectual property according to typical security policies, restricting both regular users and ASoT administrators. The ASoT must revoke access when required, and stakeholders must be able to verify the access permissions for their own artifacts.	3468: The organization owning the information shall define security policy protecting digital artifacts according to their information sensitivity. 3432: The ASoT shall implement security policy protecting digital artifacts according to their information sensitivity.
Authoritative State (User Story 2595)	The ASoT must support virtual integration of digital artifacts. The Government Program Manager (PM) for the system of interest defines what is authoritative for that system, but the PM may not own or control all of the artifacts so designated. Some artifacts may be owned or controlled by other Government PMs or outside suppliers, each with their own ASoT to manage the artifact. As a result, the ASoT for this PM may be a distributed collection of ASoTs that this PM designates authoritative at a given point in time. Regardless of the composition, the PM views its ASoT as a single, centralized repository that documents the design authorized for virtual integration along with evidence generated by approved analysis tools that the design obeys its constraints and that the design reflects an as-built system that will pass certification and the corresponding analysis results.	3452: The ASoT shall provide a version control system for storing and managing digital artifacts. 3463: The ASoT shall provide a means to associate one or more certifications with a specific version of a model artifact.
Traceability (User Story 2545)	To support certification/qualification, the ASoT must generate evidence that the system analyzed is the system as-built. While a change control system provides some benefits, a typical change control system may not track all required relationships. In particular, a change control system tracks individual artifacts, but the ASoT should also be capable of tracking the processes that produce those artifacts and the resulting analyses of those artifacts. The ASoT needs to track the use of government template models by performers, and track the tools that produced analysis results. The ASoT must track functional and performance specifications and relate similar but distinct artifacts. The ASoT should inform stakeholders automatically of actions affecting artifacts they own or control. The ASoT must repeat analysis of evolving artifacts and be able to compare different analyses of the same artifact over time. Finally, the ASoT must support discovery of artifacts through these traceability links.	3459: The ASoT shall provide a means to associate a set of analysis results with specific versions of analysis tools. 3460: The ASoT shall maintain a registry of approved modeling and analysis tools, supporting different versions thereof. 3496: The ASoT shall notify the owner of digital artifacts of changes in automated analysis results for those artifacts.

Technology	Purpose	Requirements Elicitation	Demonstration One	Demonstration Two	Demonstration Three
DOORS NG	Requirements Management	■	■	■	■
Django	Web Framework	■	■	■	■
Magic Draw	SysML Modeling		■	■	■
GitLab	Version Control		■	■	■
Teamwork Cloud	SysML Version Control			■	■
Syndeia	Artifact Synchronization			■	■
OSLC	Model Interoperability			■	■
OSATE	AADL Modeling and Analysis			■	■
CAMET	Model Analysis			■	■
Jenkins	Continuous Virtual Integration			■	
OpenMBEE	Model Management and Reporting			■	
ARAS	Product Lifecycle Management				■
Neo4J	Graph Database				■

A filled box indicates we used the technology in the activity

Figure 2: Tools used for various aspects of ASoT demonstrations

We elicited user stories from interviews with DoD stakeholders and Capstone performers, and from surveys of existing research. From these interviews and a review of prior research on ASoT, we collected 170 user stories describing ASoT use in twenty-five stakeholder domains. To distill requirements from these user stories, we refined our terminology enough for the requirements to be actionable. We collected and refined a collection of terms, all of which we provide in our long-form report. For example, we created a simple definition of an ASoT that reflects its value as a repository of system artifacts and relationships.

An Authoritative Source of Truth is a capability that gives definitive answers to queries about a target collection of systems.

We also identified a simple term to represent the atomic contents of an ASoT.

A digital artifact is a specific, unique, and immutable piece of information. A digital artifact has a fixed length and fixed internal structure.

As shown in Figure 1, an ASoT is a capability (composed of a combination of tools, people, processes, and rules) that gives definitive answers (backed up by business rules for the relevant organization) to queries (requests for information) about a target family of systems. The answer to a query comes in the form of digital artifacts.

3.0 ASOT REQUIREMENTS

From these user stories and these terms, we derived 123 use cases, from which we derived 103 requirements (you can find a link to these at the conclusion of this article). The requirements enumerated ASoT support across fourteen capability categories: access control for digital artifacts, authoritative state definition, autonomous operation of the ASoT itself, certification of fielded systems, collaboration across ASoTs and stakeholders, configuration control for digital artifacts, custom views of current state, metadata collection, queries, re-compete of digital artifacts, resilient operation of the ASoT itself, traceability of digital artifacts, tradeoff analysis between design alternatives, and workflow definition. We shared these requirements Army stakeholders and Capstone performers, and we incorporated their feedback. The long form of our report includes the Capstone performer feedback and the Army's prioritization of the user stories. The Army identified fifteen high priority user stories, with the most critical in the areas of access control, authoritative state, and traceability. Table 1 provides descriptions of these three categories (we provide descriptions of the other categories are in the full report).

The requirements also provided the objectives for three demonstrations. Each demonstration showed an assortment of tools and technologies targeting selected ASoT requirements. Demonstration one focused on requirements management. Demonstration two focused on analysis and change propagation. Demonstration three focused on traceability and defining a digital thread across multiple repositories. Figure 2 summarizes the tools applied for each demonstration.

We conducted our demonstrations using an open-source FireSat SysML (From Friedenthal and Oster, http://sysml-models.com/spacecraft/models.html) model as a starting point, from which we built and expanded a systems engineering scenario. Our Army customer indicated that their highest priorities for demonstration were security and traceability. We defined notional stakeholders and used the tools shown in Figure 2 to demonstrate methods for conducting engineering activities among multiple stakeholders, with a specific emphasis on security and traceability capabilities of the tools. For example, we demonstrated traceability from requirements in DOORS NG to MagicDraw to Architecture Analysis and Design Language models in OSATE.

We found that the capabilities to meet

ASoT requirements are available in commercial and open-source tools, but that the integration of tools from multiple vendors into workflows required non-trivial effort. For example, Open Services for Lifecycle Collaboration (OSLC) is a standard that provides mechanisms for integration of multiple tools, but vendor adoption of OSLC is not uniform.

These demonstrations provided a reference point from which to establish generalized recommendations for DoD and industry stakeholders who will own, assemble, or use an ASoT. Although we did not have time or budget to exercise all of the ASoT requirements, we were able to establish an understanding of existing tool capabilities such we can make the following recommendations with confidence that they are feasible.

4.0 RECOMMENDATIONS FOR ASOT ACQUISITION AND ASSEMBLY

We draw our recommendations from the results of our demonstrations and from the same source material used to generate the ASoT requirements: user stories, interviews with industry and US government subject matter experts, surveys on existing practice, and prior research. At the acquisition planning stage, the DoD should identify documents that may need tailoring to include ASoT procurement for a program. Internal government documents, such as the System Engineering Plan (SEP), should address engineering tools and data delivery methods including products and licenses required for the ASoT. The technical review section of the SEP should address how information such how stakeholders will use models in the ASoT for review and document generation. The DoD should include the requirements for the use of an ASoT in a program during the Request for Proposal (RFP) planning stages.

Our recommendations fall into three categories: things to acquire and store in an ASoT, things to communicate to other stakeholders who will access that ASoT, and considerations for assembling an ASoT. We examined our sources for situations in which, in order for the DoD to achieve its objectives, the DoD must acquire something from its suppliers to store in its own ASoT.

What to Acquire

When acquiring digital or physical resources, procurement staff should address the following needs:

- Acquire the digital artifacts the DoD needs to approve and recompete the fielded system. “Knowing what you know” was a recurring theme in our discussions with stakeholders; data does no good if you cannot find it or do not have the rights to use it. Digital artifacts that the DoD requires to recompete the system should exist within an ASoT that is under the DoD’s control. Mark the digital artifacts approved for integration, and associate with each digital artifact the evidence that justifies that approval. Track the system throughout its lifecycle to identify the as-approved, as-built, as-maintained, and as-destroyed versions of the system. Acquire models to represent legacy components.
- Acquire the data rights for each digital artifact that the DoD stores in the ASoT. Data rights were a major concern for both industry and Government stakeholders. Government needs to procure sufficient data rights to provide flexibility, while also protecting the intellectual property performers. Consider technical data, computer software, and computer software documentation data rights and communicate the DoD’s desired rights in the solicitation for each procurement based on the TD and CS strategy according to Defense Federal Acquisition Regulations Supplement (DFARS) 207.106 in the Acquisition Planning Phase of the procurement. The Statement of Work and CDRL should identify negotiated data rights for each digital artifact to be delivered in the ASoT.
- Acquire required metadata for each digital artifact needed in order to support access control, search, approval, and recompete. Develop and adhere to a standard for the metadata collected. The ASoT requirements call out collecting artifact expiration dates, country-of-origin, country-of-delivery, information criticality, non-functional requirements such as manufacturing constraints, and cost and scheduling metrics. The ASoT requirements also call out evidence to demonstrate the provenance of digital artifacts, such as the tools used to build or generate the artifact, the contract guidance used to produce the artifact, marking and licensing information (even from previous contracts), template models used to produce the artifact, and analysis results and certification results associated with specific versions of the artifact.

What to Communicate

When engaging with stakeholders about a new or ongoing DoD procurement activity, the owners of the ASoT should communicate the following expectations:

- Communicate the approved tools that the DoD will require stakeholders to use. Communicate these selections in the solicitation and/or Statement of Work. The ASoT requirements call out the need for a registry of approved modeling and analysis tools and the need to store the model analysis results in a systematic way that supports examination by subject matter experts.
- Communicate the types of digital artifacts that the ASoT will manage. The ASoT requirements provide examples such as models associated with legacy components, DoD template models, models developed under the performance of this contract, and government-furnished information.
- Communicate data rights and distribution marking policy for all types of digital artifacts that the ASoT will manage. Communicate the granularity with which markings are to be applied within diverse types of artifacts. For example, policy might call for data rights markings applied at the level of blocks in a SysML model.
- Communicate the approved representations for each type of digital artifact. Adopt and adhere to a set of approved representations (languages, formats) to facilitate interoperability between different ASoTs and to simplify the recompete of any digital artifact. During our demonstrations we found that contemporary tools can manage and relate different data representations, but to configure and maintain these tools requires engineering effort. For example, we were able to automate synchronization between a requirements database and a SysML model, but configuring the network connections, authentication, and customized settings required for each tool required engineering effort .
- Communicate the security policies that will enforce authorized access to digital artifacts stored in the ASoT. Stakeholders contributing digital artifacts to the ASoT should understand how the ASoT will protect those artifacts. The ASoT requirements call for security policies addressing, for example, information sensitivity, contractual rights, and organizational role.
- Communicate the change management system within the ASoT that will manage digital artifacts. The ASoT requirements call for a change management system, including each stakeholder’s role therein, that includes issue tracking and resolution, comparing and merging different versions of an artifact, and staging proposed changes for approval before submission.
- Communicate the planned execution of DoD-selected operations over digital

artifacts. The ASoT requirements include calls for the ASoT to query and visualize artifact associations, to schedule automatic execution of user-defined analysis over artifacts, to notify the artifact owner of changes, and to facilitate translation of artifacts to alternate representations or languages. During the demonstrations on this study, as well as in the Joint Multi-Role Mission System Demonstration as a whole, we found that early communication of planned analysis is critical to ensuring that digital artifacts contain the necessary information in the necessary format for analysis (See our prior work on inter-organization virtual integration: https://www.sae.org/publications/technical-papers/content/2018-01-1944/).

- Communicate the interfaces approved for access to other stakeholder ASoTs, such as OSLC. Our tool survey revealed that of the two common approaches for tool integration (either build a custom interface or build to a common standard), building to a common standard is more scalable and better supports future capabilities.

What to Assemble

When constructing an ASoT or maintaining an existing ASoT, the ASoT owner should embrace the following guidelines:

- When purchasing tools to assemble an ASoT, consider the costs and risks of changing tools in the future. Consider whether individual components in an ASoT are individually replaceable. Tools that support standardized, interoperable data representations and interfaces provide flexibility and enable the "credible threat of re-compete" for the ASoT itself.
- Establish a consistent approach towards the definition of equivalency relationships within the Model Based Engineering Environment. Specifically, a rigorous process must be in place to establish equivalency relationships, and to modify or remove equivalency relationships when associated artifacts change, undergo versioning, or are removed. Without a consistent process, equivalency relationships can become confused, corrupted, or lost, leading to unreliable traceability throughout the ASoT implementation.
- Invest in open standards. To meet engineering objectives an organization may need to use multiple tool environments. For example, an organization might use MagicDraw for a modeling environment, IBM DOORS for requirements management, and IBM Rational Change Management for change management. Any significant engineering effort generates a vast amount of data, with data overlapping in representation and storage. An ASoT should integrate accumulated data so that query operations can traverse data relationships. For example, an organization may wish to integrate MagicDraw and DOORS by enabling access to DOORS information from the MagicDraw tool environment. OSLC is one open standard approach to achieve such tool integration. In demonstration two we demonstrated use of Intercax Syndeia to transfer requirements between DOORS and MagicDraw.

5.0 CONCLUSIONS

The major systems procurement environment is moving away from siloed, sole-source systems to systems composed of modular components from multiple organizations. The artifacts associated with these systems are similarly evolving to provide increased modularity and portability. To manage these design artifacts, we need a capability to provide definitive answers to queries about the systems. This capability comes from an authoritative source of truth. We created a set of requirements for an authoritative source of truth, then demonstrated approaches to meeting those requirements. We generated guidance ASoT users and stakeholders, such as procuring systems with the authoritative source of truth in mind, being mindful of artifact identity, and investing in open standards for connectivity between tools.

The long form report for this study (which includes the ASoT requirements in appendix A) is available at https://www.adventiumlabs.com/publication/authoritative-source-truth-study ■

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Charles Payne has over thirty years' experience performing computer security research at industry and government laboratories. He is currently the technical lead of development teams producing cybersecurity analysis tools supporting the US Army's Model-Based Systems Engineering (MBSE) activity for future mission systems. These tools reduce the cost and effort to qualify systems against US Department of Defense (DoD) cybersecurity standards, including the Risk Management Framework (DoDI 8510.01) and Cross Domain Policy (DoDI 8540.01).

John Shackleton has over twenty-five years of engineering experience, specializing in real-time embedded systems, model-based engineering, and cybersecurity. Since 2013 he has served as the principal investigator for several Adventium Labs research projects. John is currently leading the effort on the DARPA Cyber Assured System Engineering (CASE) program, subcontracted to Collins Aerospace, to develop an automated AADL-based build environment for unmanned vehicle platforms. Additionally, John was the technical lead for the Adventium ASoT study, responsible for developing a series of prototype demonstrations that highlight particular ASoT requirements.

Creating the Digital Thread

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ABSTRACT
In this article the author defines the digital thread and related terms. The author discusses the topics of disparate data sources and interdisciplinary traceability, relative to digital engineering. The author offers approaches to creating the digital thread, including detailed explanations of trace link properties. The author explains an example digital thread from a sample United States Army program and presents guidance for creating and using digital threads.

KEYWORDS: digital thread, digital engineering, trace link, traceability, artifact, model element

INTRODUCTION

The digital thread is a powerful tool and an integral part of digital engineering. To understand the digital thread, it is important to first define what is meant by "digital engineering," as well as several of the common terms associated with it. Digital Engineering may be defined as the combination of model-based techniques, digital practices, and computing infrastructure to enable the delivery of high pay off solutions. These techniques and practices often include the use of computer-aided design (CAD) models, system architecture models, requirements documents, system analysis models, product lifecycle management (PLM) programs, and many other types of models, documents, or software tools. These models and the model elements that comprise them are then integrated together to form the overall digital representation of the entire system.

Some additional key terms often discussed in the field of digital engineering are defined as follows:

Artifact – Any document, file, model, model element, or other piece of data or information that can be considered as its own entity with a distinct set of properties, within the digital engineering environment.

Authoritative Source – A managed repository of valid or trusted data that is recognized by an appropriate set of governance entities and supports the governance entity's business environment.

Digital System Model – A collaborative product of systems engineering and design engineering efforts.

Digital Thread – The aggregate of a product's artifacts and their relationships, captured as trace links, over the course of the product's lifecycle.

Digital Twin – A software representation of each unique physical asset for each manufactured product. That is, for each physical part produced, there exists a corresponding software representation known as its digital twin. Likewise, for each physical system produced, a digital twin of the system may exist, comprised of the digital twins the system's physical components.

Model – A representation of a system, part, or process that is used to replicate key attributes of the system, part, or process.

Model Element – A component of a model that can also be considered as its own entity with a distinct set of properties.

Trace – A relation between two artifacts.

Trace Link – A digital representation of a trace connecting two artifacts in a digital engineering environment.

BENEFITS OF IMPLEMENTING DIGITAL ENGINEERING

Digital engineering addresses the problems of disparate data sources and traceability by providing an integrated data-sharing environment that connects authoritative data and project artifacts across the program and potentially across the entire enterprise.

A common problem that is addressed by digital engineering is the use of disparate data sources. Programs will often use a number of different data sources such as shared network drives, local hard drives, product lifecycle management (PLM) programs, and other managed data repositories to manage their design and design-supporting data. In fact, it is common for programs to have multiple authoritative data sources for the different types of program artifacts, such as requirements documents, system architecture models, or computer aided design (CAD) models. This approach leads to siloed information, which can inhibit effective communication and team collaboration on projects if the information is not thoroughly disseminated to the project members regularly. The use of an integrated data-sharing environment addresses this problem by providing all project artifacts in a single location, allowing project members to access the authoritative project data when they need it.

In addition to disparate data sources, a lack of traceability is also a major problem on many programs. The entirety of a program's data consists of many documents, models, and other project artifacts that relate to one another. Traceability serves as the means of managing those relations between project artifacts in a formalized and consistent manner. Just as a research paper must contain reliable references to well-founded sources, project artifacts must be traced to authoritative sources to ensure that they are valid. These trace links must be documented to keep a record of each project artifact's sources, as well as regularly analyze these relations to ensure the continued validity of the artifact as both it and its sources are revised. However, many programs fail to document these trace links, making it difficult to determine which project artifacts are valid and necessary, and which ones are not. Furthermore, many programs that do document these trace links do so using static tables or matrices, which do not support the analysis of these relations based on changes to either the artifact or its sources. Digital engineering environments address this problem by using trace links to document the traceability between project artifacts. Each trace link represents a single unidirectional relation between two artifacts. The aggregate of all trace links across a project forms the digital thread, which can be analyzed to provide insight into the system as a whole.

APPROACHES TO CREATING THE DIGITAL THREAD

Creating the digital thread begins with establishing traceability between project artifacts using trace links. These trace links have several properties that must be clearly understood before attempting to create and analyze the digital thread.

- A trace, modeled by a trace link, is the most general representation of a relation between two artifacts and can be further categorized by specific types of relations. The full suite of relation types that may be used on a given project will depend on the modeling methodology and software tools used by the enterprise. However, some common relation types include Composes, Defines, Refines, Satisfies, Verifies, and Validates.
- A single trace link expresses a distinct relation between two artifacts. Every relation is represented by a single trace link; therefore, if more than one relation exists between two artifacts, each relation shall be modeled by its own trace link. Additionally, a single trace link cannot be used to represent a relation spanning more than two artifacts, but rather multiple trace links shall be used to represent all present relationships between distinct pairs of artifacts.
- Trace links are unidirectional, meaning they are made from one artifact to the other. Often, the start-point of the trace link is the subject artifact, while the end-point is the object artifact. This notation is shown in Figure 1, where the artifacts are depicted as boxes and the trace link is the arrow connecting them.
- Trace links exhibit the transitive property. For example, if a relationship exists between artifacts A and B, and a relationship exists between artifacts B and C, then an implied relationship exists between artifacts A and C. This property is what makes the digital thread such an important tool for analyzing the project-wide impacts associated with making changes to specific project artifacts.
- Trace links exhibit the reflexive property. That is, if a relationship exists between artifacts A and B, then an equal and opposite relationship exists between artifacts B and A. For example, if artifact A has a "verifies" relation to artifact B, then it could also be said that artifact B has a "is verified by" relation to artifact A. However, for reasons discussed later in this paper, it is best practice to model only one such relationship using a single trace link whose directionality is consistent with the project's defined modeling practices.

Figure 1. Unidirectional trace link

There are several common ways to view and create trace links to form the digital thread. The available methods will depend on the specific software tools and modeling methodology. While the specific nomenclature and graphical user interface will vary for different software tools, the concepts discussed here are consistent across all digital engineering platforms.

Trace links may be viewed as (1) properties of a selected artifact, (2) in tabular format, (3) in a matrix format, or (4) in a graphical representation.

(1) Each project artifact has its own set of properties, or attributes, that provide supporting information about the artifact, such as creation date, last modified date, or data owner. A common attribute of artifacts in digital engineering environments is the list trace links of the given artifact, sometimes separated into two attributes for incoming and outgoing trace links respectively.

(2) Tables are typically used to show the trace links of a common set of artifacts. For example, a requirements document is comprised of several requirement statements, each of which may be considered as its own artifact. A table may be used to list the requirement statements contained within the document along with their respective trace links.

(3) Matrices are typically used to show trace links between two common sets of artifacts. For example, physical system components may be traced to system functions, where each component and each function is its own artifact. To show this traceability in matrix form, the list of components would occupy the rows while the list of functions occupies the columns of the matrix, or vice versa. Here, a trace link between a specific component and function is represented by an arrow in the matrix cell where the component and function intersect.

(4) Graphical representations of trace links typically vary the most among different software tools. However, artifacts are commonly represented as boxes and trace links are shown as arrows connecting the various artifacts displayed in the graphical view. The boxes representing the artifacts shall contain, at a minimum, an identifier such as the artifact name or identification number. Many programs will often use different box colors or styles to represent different types of artifacts and different arrow colors or styles to represent different types of relations.

Trace links may either be created manually by the user or automatically based on rules defined in the software tool. Commonly, both the manual and automated methods of creating trace links are used in unison to ensure full traceability across all project artifacts.

One can create trace links manually by selecting the artifacts that will comprise the start- and end-points of the trace link and then executing the tool-specific software function to create the link between them. Typically, users can create trace links from any of the traceability views described previously, so long as the user can select both the start- and end-points. Additionally, many software tools offer the ability to create several trace links simultaneously by selecting a single start-point and multiple end-points, or multiple start-points and a single end-point, for the trace links to be created.

Trace links may be created automatically when the software tool has a defined set of rules for creating trace links between artifacts based on specific conditions and/or user actions. Many tool- and organization-specific use cases involving the automatic creation of trace links can be defined. However, some common examples are data imports from a data management system with previously defined trace links, the creation of a new artifact based on an existing artifact, and the use of workflows to track and manage project activities.

iMBE IMPLEMENTATION

The United States Army's DEVCOM

Armaments Center (AC) began a digital engineering initiative known as integrated Model-Based Engineering (iMBE) to further expand the command's digital engineering capabilities and enable the creation of the digital thread across all project artifacts. The capabilities of the iMBE digital engineering environment were demonstrated using a miniature catapult system, shown in Figure 2. While the catapult system itself is overly simplistic, the artifacts and methodology used to create the digital thread are representative of the actual processes employed by DEVCOM AC.

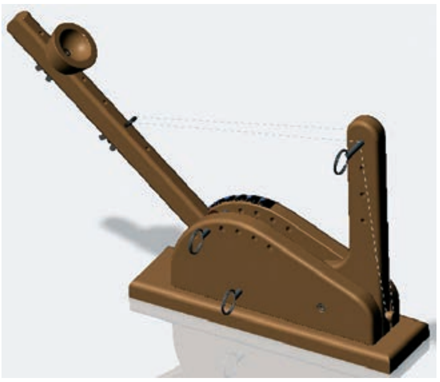

Figure 2. CAD model of the sample catapult system

The catapult project consists of 40 top-level artifacts, which include requirements documents, a system architecture model, CAD models and drawings, simulations and analysis models, and other supporting documents. Here, the term "top-level" refers to the level of data granularity, where each top-level artifact is not part of, nor contained in, any other project artifact. For example, the system architecture model is the top-level artifact that contains lower-level artifacts such as modeling diagrams, which contain even lower-level artifacts such as blocks or activities; however, the system architecture model itself is not part of any larger model or artifact. These various levels of data granularity within a system model, or any other complex artifact, are also known as levels of abstraction.

There are 91 sets of trace links relating these 40 top-level artifacts to one another, where each set contains one or more individual trace links. Here, a set of trace links is defined as a group of trace links representing the relations that exist between two top-level artifacts and/or between the sub-elements of those two artifacts. For example, the catapult project's system requirements are traced to the stakeholder needs statements. The system requirements and stakeholder needs are both represented by their own top-level document; however, the individual requirements and needs statements are also their own lower-level artifacts. Therefore, the trace links are created at the requirement/need statement level of abstraction, and not at the top level between the two documents themselves.

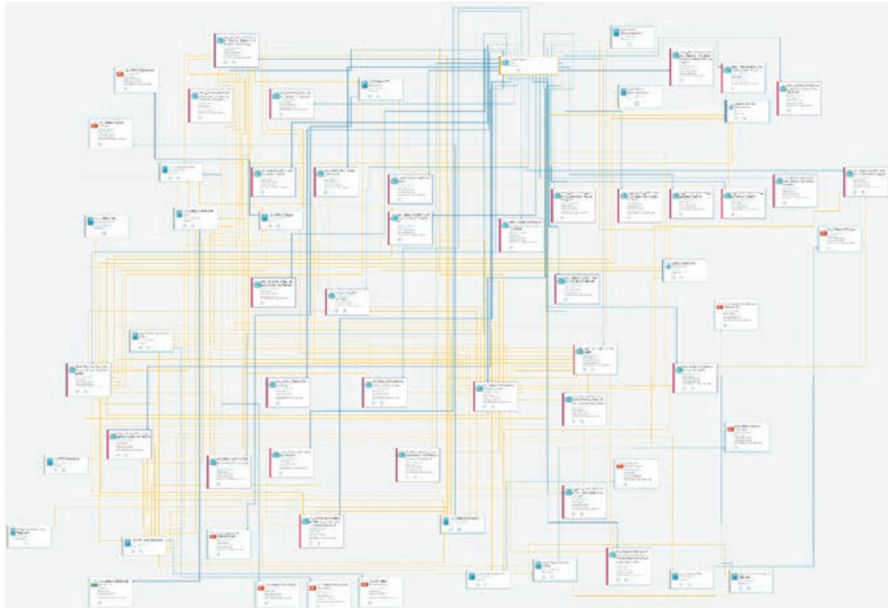

Figure 3. Digital thread of the sample catapult system

The top-level catapult system artifacts, as well as several lower-level artifacts, and the trace links between them are shown in Figure 3. This figure provides a graphical representation of many of the trace links between the major catapult artifacts. These trace links form the digital thread for the catapult system. Here, the yellow arrows represent trace links, and the blue arrows represent containment relations between artifacts at different levels of abstraction.

From the digital thread excerpt of the catapult system shown in Figure 3, it is evident that the numerous relations between project artifacts can be quite cumbersome or even impossible to manage without a formalized traceability management system in place, even for a simple project such as the catapult. It is important to bear in mind that the figure only depicts the trace links between the top-level artifacts. To expand the view to show trace links between artifacts at lower levels of abstraction would increase the size and complexity of the figure by full orders of magnitude. For this reason, the graphical view by itself is not a practical means of following the trace links of multiple artifacts or of a particular artifact beyond more than two or three levels of traceability. Here, "levels of traceability" refers to the layers of subsequently traced artifacts, following the trace links from one artifact to the next. While a graphical representation may be suitable for viewing the trace links going to and/or from a single artifact, expanding the trace links of the subsequently traced artifacts quickly clutters the view and makes the image unreadable. For this reason, it is desirable for the user to have the capability to perform an impact analysis, wherein a specific artifact is selected, and the user generates a report showing all the artifact's trace links across several levels of traceability.

The iMBE environment provides the capability to generate an impact analysis report, in which trace links of a selected artifact are listed in tabular format for all levels of traceability. For example, if the impact analysis report is generated on artifact A, and artifact A is traced to artifact B which is then traced to artifact C, then the report would list the relation between artifacts A and B as well as the relation between artifacts B and C, and any subsequent relations beyond that. The report is also sensitive to the trace link direction, meaning that it can be generated on either incoming trace links or outgoing trace links, but not both.

GUIDANCE FOR CREATING AND USING DIGITAL THREADS

When creating and using the digital thread of a system, there are several modeling techniques and best practices to consider. Some of these practices include defining a consistent trace link direction, creating trace links at appropriate levels of granularity, and investigating the impacts of

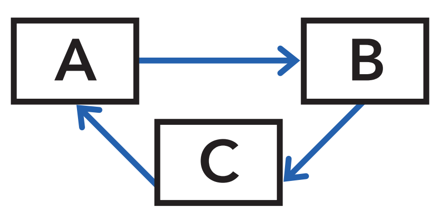

Figure 4. Trace link loop

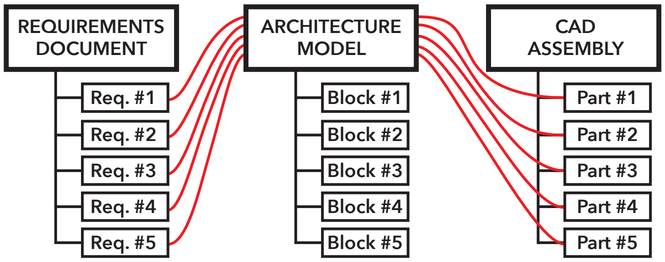

Figure 5. Digital thread with bottleneck

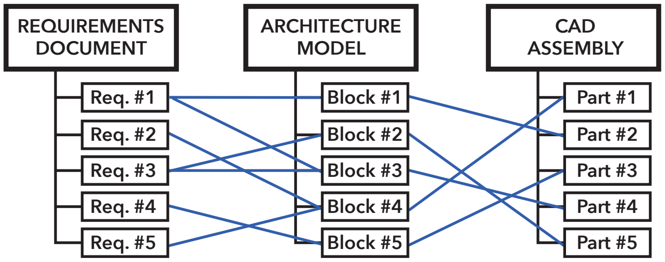

Figure 6. Digital thread without bottleneck

potential changes to artifacts.

Trace links should be created with consistent directionality across all project artifacts to ensure that relations between artifacts can be clearly understood by project members and stakeholders. Additionally, only one trace link should be created for each relation, and not its reflexive pair, so that loops are not created in the digital thread. Creation of a loop occurs when the end-point of a chain of trace links returns to its originating starting point, as shown in Figure 4. Such loops can be problematic when generating a traceability report, such as the iMBE impact analysis report, because they create a continuous chain with endless layers of traceability. By defining a consistent trace link direction across all project artifacts, project members and stakeholders can clearly view the flow of information across artifacts and avoid creating loops in the digital thread.

Trace links should also be created at the appropriate level of granularity. Typically, establishing trace links at lower levels of granularity (fully decomposed model elements) produces a more insightful and meaningful digital thread, but also requires more work upfront. Conversely, establishing traceability at higher levels of granularity (documents and top-level models) requires minimal work upfront, but does not yield a useful digital thread. For this reason, it is recommended that projects establish traceability at the lowest level of data granularity for which it is practical to model. Common examples of low-level artifacts that may trace together are requirements, are CAD parts or parameters, finite element analysis (FEA) results, and system architecture elements such as blocks, activities, and functions.

Additionally, when creating a trace link between two artifacts, the artifacts should be at comparable levels of abstraction. For example, a system architecture block may be traced to a requirement, or FEA results may be traced to a CAD model. However, if one artifact is traced to another at a much higher or lower level of granularity, then a bottleneck may be created in the digital thread, as shown in Figure 5. Such bottlenecks prevent project members from extracting useful information from the digital thread by flooding traceability reports with extraneous artifacts. For example, if a traceability report were executed on Part #5 in Figure 5, the report would show that the part is traced to the architecture model, which is traced to all five requirements; however, this does not provide any useful information regarding which requirements are applicable to Part #5. If, however, the trace links were made to the appropriate blocks as opposed to the overarching architecture model, as shown in Figure 6, then useful information can be ascertained from a traceability report showing which requirements apply to which parts.

Lastly, it is a best practice to use the digital thread to investigate the impacts of potential changes to project artifacts. Depending on the capabilities and software limitations of the digital engineering environment, these investigations can be done automatically or manually with traceability reports. As discussed previously, users export traceability reports of the digital engineering environment and the reports show all the trace links of a selected artifact. For digital engineering environments in which changes may be detected automatically, users are typically notified when any changes occur that could potentially impact an artifact that the user subscribes to or owns. It is important to note that making a change in an artifact does not necessarily require the related, or traced, artifacts to change as well. Whether or not the traced artifacts will be required to change is still a decision for the project members to make. The digital thread merely serves as a tool that project members can use to identify all related artifacts when assessing what changes need to be made to project data. ■

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Michael Toriello served as the systems engineering lead (SEL) on the United States Army’s integrated Model-Based Engineering (iMBE) program. During his time in this position, he conducted research in creating and using digital threads, provided demonstrations displaying traceability analyses, and developed and managed requirements for instantiating digital engineering environments. Mr. Toriello received his bachelor’s degree in mechanical engineering from the New Jersey Institute of Technology (N.J.I.T.) in 2019 and his master’s degree in mechanical engineering, specializing in thermo-fluid systems and energy, from N.J.I.T. in 2020.

Distributed Cross-Domain Link Creation for Flexible Data Integration and Manageable Data Interoperability Standards

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ABSTRACT
A distributed link creation strategy represents a shift from the traditional centralized link creation strategy used for data integration. A distributed link creation strategy provides a more flexible, user-friendly approach for engineers to specify cross-domain links between different domains of engineering data, which is key to achieving traceability across different product lifecycle phases. A new type of API that allows API clients to find link targets easily and create links makes this possible. Features of this new link-enabling API include support for the open-world assumption, embeddable search dialogs, and hypermedia for self-discovery. Furthermore, a distributed link creation strategy also supports more efficient standardization efforts to achieve data interoperability by only requiring small, thus more manageable, domain-specific standards in combination with standardized cross-domain links, in contrast to the typically large, therefore unmanageable, multi-domain standards.

1. INTRODUCTION

As shown in the figure below, one achieves traceability across engineering domains by linking engineering data: such as from requirements to simulation results. Linked data helps engineers understand how requirements have been tested and satisfied. Linked data is critical for performing impact and root cause analysis. Linked data also helps engineers understand when simulation models need to run again with newly updated data, as well as the correct sequence in which simulation models should execute as outputs are sometimes the inputs of others.

Linked data is composed of engineering data authored in specialized engineering software applications as well as of cross-domain links which should be available in a neutral format for reuse for many different purposes. These links are the glue that

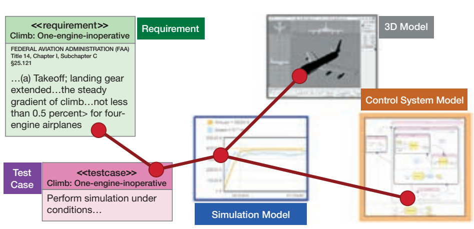

Figure 1. Example of cross-domain relationships between engineering data objects across the product lifecycle to achieve end-to-end traceability

connects various engineering domains to enable organizations to design consistent, complex systems.

A cross-domain link by itself is simple. As shown in the figure below, it only consists of three parts identified through unique global identifiers: a link source, a link target, a link type. Links are relationships with direction.

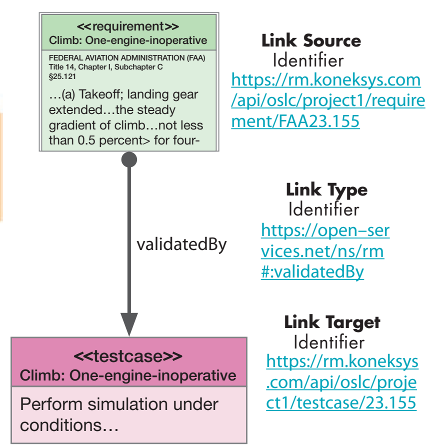

Figure 2. Cross-domain link defined as a unidirectional link identifying the link source, target and link type using unique global identifiers

2. CENTRALIZED CROSS-DOMAIN LINK CREATION

Defining a cross-domain link is very easy on paper. However, in practice, engineers currently define cross-domain links in specific centralized applications (ex: PLM/ALM/MBSE solutions) as shown below. Engineers use a PLM solution to define links in mechanical engineering, an ALM solution for links in software engineering, and an MBSE solution for links in systems engineering. The links often save in proprietary data formats, preventing analysis of these links in a larger global context.

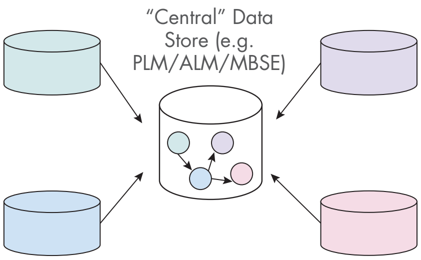

Figure 3. Centralized approach for creating and managing cross-domain links within a single application requiring the import of data from other data sources

Data integration applications like PLM, ALM, and MBSE describe many different aspects of a system. They also provide tools for the visualization and analysis of cross-domain links. The issue is that the engineers must create cross-domain links within specific data integration applications and not in the domain-specific applications, which are much more familiar to most engineers. It is a lot more user-friendly for an engineer to create a cross-domain link from within his domain-specific application than having to switch to another "centralized" data integration application.

Furthermore, existing data integration applications (ex: PLM/ALM/MBSE) often only support integrations with specific data sources either due to vendor lock-in policies, or simply because a data import adapter is not available for every data source. Aerospace companies designing complex systems can, for example, use more than 500 different engineering software applications. All these applications use different data formats and programming interfaces, thereby representing a multitude of diverse data sources. Without standardizing the interfaces of these 500+ different engineering software applications, it is impossible for any software vendor to integrate their data in a single application.

Until now, standardization organizations, as well as vendors have assumed that cross-domain links needed definition within a single application conforming to a single "universal" schema. Engineers have therefore defined "universal" data schemas, such as STEP AP39 (ISO 2012, http://www.plcs-resources.org/ap239/) or STEP AP 243 (ISO 2021, http://www.mossec.org/), for describing data from many different domains and applications in a common format in conformance to a single schema. These "universal" standards have not undergone adoption by software vendors because they are too large in scope. The larger the scope of a schema is, the harder it is for vendors to support it, and the harder it is for standardization organizations to agree on necessary updates for keeping such schemas relevant.

So, in practice, large organizations are typically defining cross-domain links in a single proprietary application with no conformance to a standardized data schema, and with limited access to data from a maximum twenty different engineering software applications instead of the required 500 different engineering software applications. Without a significant change in the data management architecture, data integration and data interoperability will remain poor for engineering data.

3. DISTRIBUTED CROSS-DOMAIN LINK CREATION

The good news is that a different paradigm in the form of a distributed link creation strategy can be a game changer. The World Wide Web serves as the perfect reference example for a distributed link creation strategy. Content creators add Web pages containing links to other Web resources in a distributed way without having to use a single application or a single "universal" schema. Similarly, engineers should not have to rely on one single PLM/ALM/MBSE solution to define cross-domain links but instead create them in their preferred domain-specific applications in a distributed and user-friendly way, as depicted below.

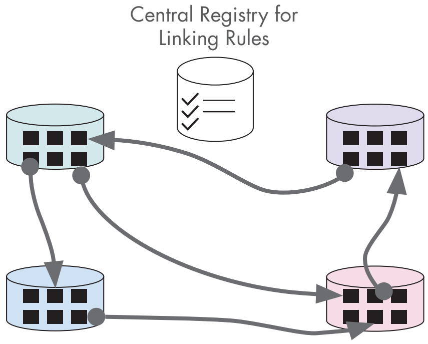

Figure 4. Distributed approach for creating cross-domain links within any application without requiring the import of data from other data sources

Engineers need restrictions when creating cross-domain links to prevent chaos. If engineers randomly define cross-domain links between data objects, it becomes impossible for an organization to understand and analyze these links at a global level. Therefore, organizations need to specify rules for cross-domain linking. For example, data objects of a certain type can only link with data objects of another type and those links will need to have a specific type. Similarly, rules already exist in the service mesh architectures to specify which microservice can talk to which other microservice.

4. DECOUPLING LINK CREATION FROM LINK ANALYSIS

Engineers can create cross-domain links in any application, and then the links can undergo analysis by many different solutions. The figure below shows several solutions to create and analyze cross-domain links. By decoupling the creation of cross-domain links from their analysis, traditional data integration applications like PLM, ALM, and MBSE can collect cross-domain links created in different sources and create more holistic analysis results based on having access to more data and more cross-domain links.

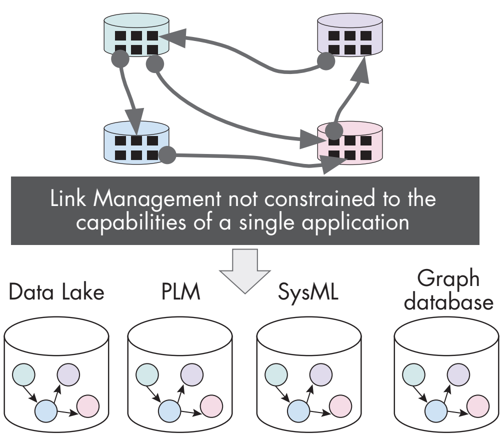

Figure 5. Decoupling between link creation and link analysis

5. PRINCIPLES OF LINK-ENABLING APPLICATION PROGRAMMING INTERFACES (APIS)

Knowledge workers, such as engineers, should be able to create cross-domain links within their few familiar software applications. A link, as defined in this context, is a typed directed relationship between two different data elements located in different data sources, namely a link source and a link target data element. From a useability perspective, a knowledge worker ideally wants to create a link without having to switch between applications to find the

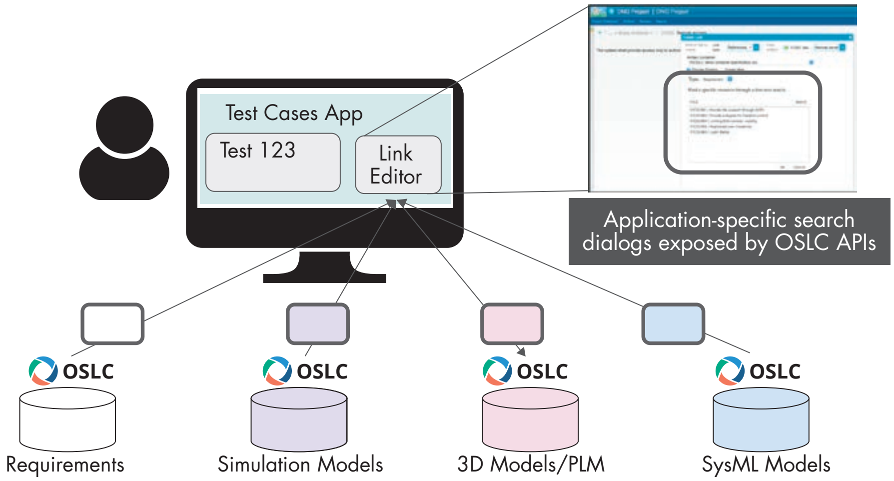

Figure 6. Application-specific search dialogs exposed by APIs in a standardized way such that human users can search and select data objects to create cross-domain links within their familiar applications

link source and link target elements, even though both source and target elements are in two different data sources. A knowledge worker can easily select one of the linked data elements within one software application but selecting the other linked data element while staying in the same software application is a challenge.

a. APIs exposing embeddable search dialogs (also known as delegated UIs)

A knowledge worker would ideally like to have a graphical search dialog for finding a link target, but this is not easy as link targets are persisted in different applications or databases that have different search capabilities. Nevertheless, each application can expose its own search capability through a standardized graphical search dialog which can be embedded, for example as HTML Iframe, within another application.

This graphical search dialog exposed by the API of each application needs to be discoverable by API clients in a standard way. Then, independent of the specific software application owning a link target, engineers can find and select link targets and create new links (Figure 6)

b. APIs exposing cross-domain links

A cross-domain link exists between a source object in a source application and a target object in a target application. When a user creates a cross-domain link, an update operation (HTTP PUT) occurs on the source object through the API of the source application.

If the update operation is successful, a subsequent read operation (HTTP GET) should return a machine-readable description of the source object containing the new link. This new link does not necessarily persist in the source application, but the API of the source application needs to make the link visible to API clients. The API of the software application exposes a new link, whereby the new link description is as a new property of the link source data element. Then, API clients can navigate across linked data elements from different APIs.

c. APIs adopting the Open World Assumption (OWA)

A traditional API only accepts pre-defined update operations to prevent chaos. In other words, a traditional API adopts a closed-world assumption to prevent unexpected, chaotic resource modifications. However, a link-enabling API, which intends to support the ad-hoc linking of objects across applications, initially needs to support any update operation. In other words, a link-enabling API should adopt the open-world assumption. Therefore, in addition to a closed-world API, applications need to also have an open-world API proxy to support ad-hoc resource modifications, provided that the modifications conform to the centrally defined linking rules. The linking rules and the APIs adopting the OWA should be decoupled, such that the APIs adopting the OWA can easily be reused in many different contexts in combination with different linking rules (Figure 7).

6. OPEN SERVICES FOR LIFECYCLE COLLABORATION (OSLC)

Engineers implemented these described principles using open standards in the form of the Open Services for Lifecycle Collaboration (OSLC 2022). Engineers used OSLC APIs to achieve cross-domain traceability by creating links within their familiar domain-specific software applications. OSLC or in general principles supporting a distributed link creation strategy allow more knowledge workers to easily create links, and thus contribute to more traceability, and to a more complete end-to-end digital thread. The OSLC community has also standardized important domain-independent aspects of linked data objects such as their configuration, associated change events, as well as associated access rules (OSLC-Core 2022), to support a global-level analysis of cross-domain links.

7. MULTIDOMAIN VS DOMAIN-SPECIFIC STANDARDS

Along with the past trend to use centralized data integration solutions (ex: PLM/ALM/MBSE), there is also the trend to define large multidomain schemas to specify the data structure for these centralized data

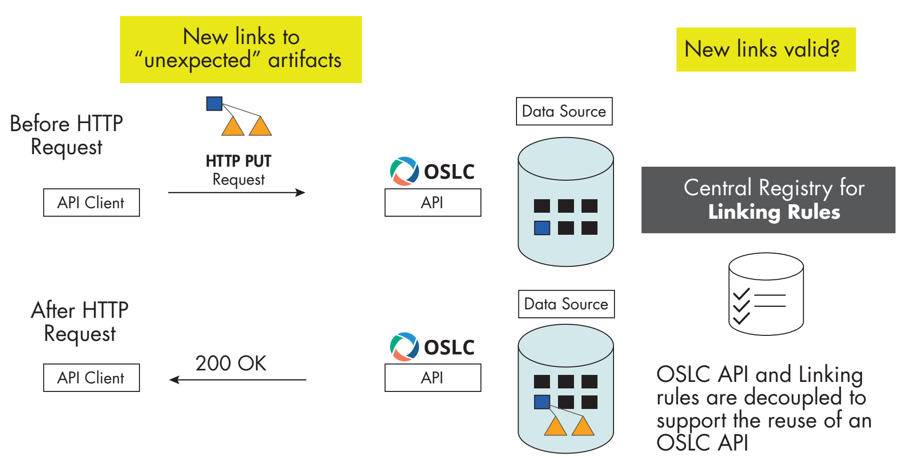

Figure 7. Link-enabling APIs, as standardized by Open Services for Lifecycle Collaboration (OSLC), supporting the Open World Assumption to support the creation of ad-hoc links to unexpected data objects, if these links comply with organization-specific linking rules

integration solutions (examples include: STEP PLCS, STEP Mossec, and SysML, and more). The larger the scope of a standard, the harder it is to achieve consensus, to maintain and update it, to keep the standard relevant, and to achieve adoption from tool vendors. That is why all multidomain standards require a lot of standardization efforts, costing a lot of money to many organizations while providing little benefit as very few tools adopt them. Furthermore, there are often significant semantic overlaps between multidomain standards, leading to unnecessary competition amongst them, which confuses end-users and vendors. Even though multidomain standardization efforts have benefited from large financial support for decades, they have not contributed in practice to improved data interoperability.

Engineers can obtain data interoperability using smaller, more manageable, domain-specific standards rather than with monolithic, multidomain standards. Since cross-domain link creation happens in a distributed way across different applications, there is no longer a need for monolithic multidomain standards. For example, most systems engineers agree that specialized tools describe requirements better than SysML. The same also applies for other SysML concepts. So, instead of defining a new version of SysML v2 that requires more than five years of standardization efforts, systems engineers should instead focus on defining domain-specific standards in combination with cross-domain standards. This strategy avoids semantic overlaps between standards and creates reduced standards in size, which in turn, can lead to faster adoption, and deliver much-needed data interoperability (Figure 8).

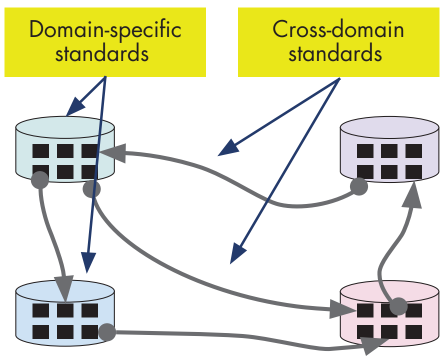

Figure 8. Smaller more manageable separate domain-specific and cross-domain standards in contrast to "universal" monolithic multidomain standards

8. CONCLUSION

Until now, data integration approaches have focused on collecting all engineering data in a single application. The business incentive of software vendors to create vendor lock-in drove this approach. Unfortunately, this approach does not scale and instead creates a bottleneck for data integration. causing a subsequent lack of end-to-end data traceability across the product lifecycle. Software vendors will not deliver the dream of a scalable data integration architecture based on open standards by magic. Instead, systems engineers and large organizations are in the best position to take a cross-domain, tool- and vendor-agnostic perspective for solving the data integration challenge in a scalable way using open standards.

The distributed creation of cross-domain links as well as the decoupling of cross-domain link creation and management sets the foundation for a radically new data management architecture which can scale, as inspired by the World Wide Web. Open Services for Lifecycle Collaboration (OSLC) defines standards in support of this new architecture based on link-enabling APIs which adopt the Open World Assumption and expose embeddable search dialogs, and cross-domain links. Furthermore, large organizations have focused their efforts on defining multidomain monolithic data schemas with no visible benefit in practice. Standardization efforts in engineering should instead focus on the definition of smaller more manageable domain-specific standards, as inspired by schema.org. ■

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Dr. Axel Reichwein developed multiple data integration solutions using Open Services for Lifecycle Collaboration (OSLC). As CEO of the software consulting company Koneksys, he helps organizations create and manage cross-domain links without vendor lock-in. Dr. Axel Reichwein is also CTO of the startup BeamDynamics where he works on knowledge graphs and graph-based AI. He received a Ph.D. in Aerospace Engineering from the University of Stuttgart, Germany, and performed postdoctoral research at the Georgia Institute of Technology in system architecture modeling and multidisciplinary data integration.

Realizing the Value Promise of Digital Engineering: Planning, Implementing, and Evolving the Ecosystem

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■ **ABSTRACT**
Gaining the benefits of Digital Engineering is not only about implementing digital technologies. The Innovation Ecosystem is a system of systems in its own right, at least partly engineered, subject to the risks and challenges of evolving socio-technical systems. This article summarizes an aid to analyzing and understanding, planning, implementation, and ongoing improvement of the Innovation Ecosystem or its components. It is based on a generic ecosystem analysis reference model with particular focal viewpoints. It is represented as a configurable model-based formal pattern and the INCOSE MBSE Patterns Working Group initially applied it in a related INCOSE collaboration project led by the Agile Systems Engineering Working Group. Users of the resulting framework subsequently elaborated and applied aspects in the context of a wide variety of commercial and defense ecosystems across different domains. While connecting to several current and historical contexts, it is particularly revealing of Digital Engineering's special promise. By explicating the recurrent theme of Consistency Management that underlies all historical innovation, it enhances our understanding of historical as well as future engineering and life cycle management. This includes the ecosystem preparation of internal and supply chain human and technical resources to effectively consume and exploit digital information assets, not just create them. The ecosystem model carries its own representation of enhanced capability implementation by generation of agile release train increments, along with evolutionary steering based on feedback and group learning.

■ **KEYWORDS:** digital ecosystem; digital engineering; digital thread; digital twin; model-based collaboration; mbse

INTRODUCTION

Many large-scale human endeavors have grown up and proliferated through the evolutionary forces of large-scale interactions and selection processes; however, as interacting systems of systems, they have not been consciously human engineered in the traditional sense. Human-performed systems of innovation include interacting elements such as competitive markets, scientific research, engineering, production, distribution, sustainment, and regulatory processes, and other life cycle management familiar to the systems engineering community (ISO 2015), (INCOSE 2015). In the natural world, systems of innovation provide a much longer history for discovery and study than the more recent human-performed cases.

The term "ecosystem," borrowed from the life sciences, has become more frequently applied to label the human-performed case, out of recognition of the vast extent, complexity, and dynamic evolution of the human-performed cases. The subject of this article is the formal INCOSE Innovation Ecosystem Reference Model, configurable across diverse specific cases. (Since this article is about a formal reference model, terms which are modeled class names from that reference model appear in title case as they appear in the named model components.)

The engineering community is certainly not without high value historical models of at least portions of the human-performed Innovation Ecosystem. The above-referenced ISO standard and INCOSE Handbook, the ubiquitous "Vee" model, DoD and enterprise-specific models, new model-based standard efforts to describe the Model-Based Enterprise, and others provide vital guidance. Out of respect for those historical assets and the importance of building upon them, we accommodate them within and mate them up with the larger-scale Innovation Ecosystem reference model's configurations referenced in this article.

Why is an ecosystem-level model needed? Smaller scale models inform teams about the work that they must perform, coordinate flows of information, plan information systems and other purposes. Is there really a need for an ecosystem level reference? Do our innovation ecosystems work well enough, and do we understand them well enough?

Ecosystem-level efforts and issues are arising that challenge our group-level abilities to effectively understand (individually and together) and communicate about the innovation ecosystem across life cycles, and particularly so while that ecosystem itself is evolving and the stakes are rising. We are increasingly interested in how to understand the basis of performance of the ecosystem as a whole (as in its timely delivery of competitive solutions) through its system components and their organization—for performance improvement, robustness, pathology, and security reasons. How do we integrate across supply chains? Are there other effective architectures besides historical OEM and captive supplier relationships? How can we improve the real effectiveness of those or other combinations? Can we even effectively communicate about this subject without a shared neutral reference model? What is the connection of the engineering community's interest with the business management community's interest in "business ecosystems" (Jacobides 2017)?

The subject of this *INSIGHT* Special Issue on Digital Engineering, along with contemporary interest in "digital twins" and "digital threads," all illustrate the growing system scope at which these needs and questions apply. The Innovation Ecosystem Reference Model described in this paper focuses on a set of ecosystem issues. Following a brief introduction to the structure of the reference model, this article summarizes these selected aspects for insight:

1. Ecosystem level capabilities' connection to underlying interactions
2. Connecting historically represented business processes to evolving digital infrastructure
3. Consistency Management's connection to realizing the promise of digital engineering
4. Effectiveness of distributed, multi-level group learning
5. Group trust in the credibility of models
6. Managing the proliferation of virtual model diversity and instances
7. Effective evolution of the ecosystem itself

SELECTED ASPECTS OF THE INNOVATION ECOSYSTEM PATTERN

We proposed the reference model in a series of papers to describe adaptive purpose-seeking innovation ecosystems (Beihoff and Schindel 2011) (Schindel 2013). It was then elaborated during a multi-year INCOSE joint project of the Agile Systems Engineering and MBSE Patterns Working Groups to study agility across a range of aerospace and defense programs by leading enterprises (Schindel and Dove, 2016), (Dove, Schindel and Scrapper 2016), (Dove and Schindel 2017), (Dove, Schindel, and Hartney 2017), (Dove, Schindel, and Garlington 2018), (Dove and Schindel 2019). Since that time, the MBSE Patterns Working Group elaborated and enhanced it to study issues listed in the introduction across other enterprises and migrated into a generic configurable S*Pattern expressed in OMG SysML. At the time of this writing, it is also applied as a reference model in a current joint project by AIAA, INCOSE, and others to study a series of Digital Twin and Digital Thread cases and principles. This article summarizes aspects of the reference pattern translated from its more detailed OMG SysML version, using accurate but less formal graphic renditions, for ease of comprehension.

Reference Model Structure

Figures 1-3 informally summarize the formal model's logical architecture, Levels 0-2, the first three decomposition levels of the logical architecture. By Level 2, these separate the roles played by ecosystem 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 configured. Prominent in this decomposition are three system reference boundaries, for defined Systems 1, 2, and 3:

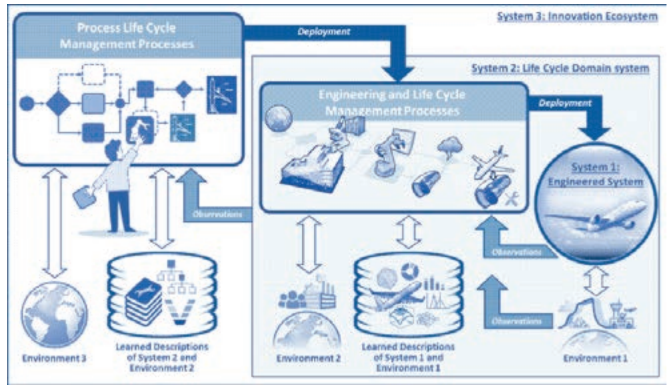


Figure 1. Level 0 logical architecture, Systems 1, 2, and 3

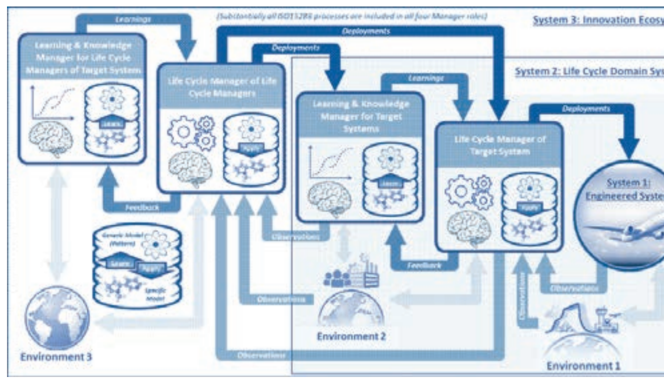


Figure 2. Level 1 logical architecture, learning versus applying

1. **System 1 – The Engineered System of Interest:** at all times in its life cycle.
2. **System 2 – The Life Cycle Management Domain:** 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 (research, engineering, manufacturing, distribution, markets, operations, sustainment, and more). System 2 is responsible to observe and learn about System 1 and its environment, not just engineer and deploy it. A model or artifact describing System 1 is a subsystem of System 2, which also includes the collaborating users of that information.
3. **System 3 – The Overall System of Innovation:** Includes the system responsible to plan, deploy, and evolve System 2, responsible to observe and learn about System 2 and its

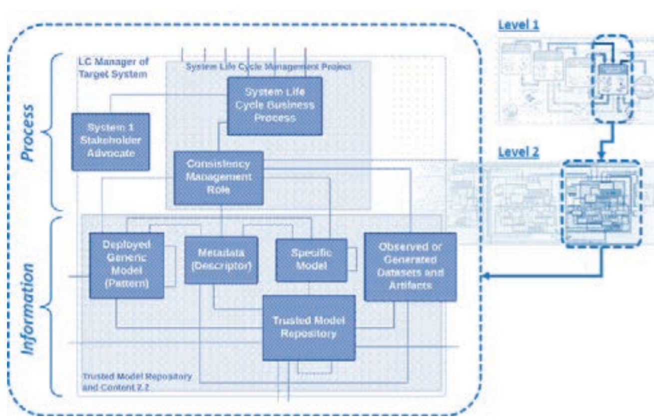


Figure 3. Level 2 of logical architecture, process roles versus information roles

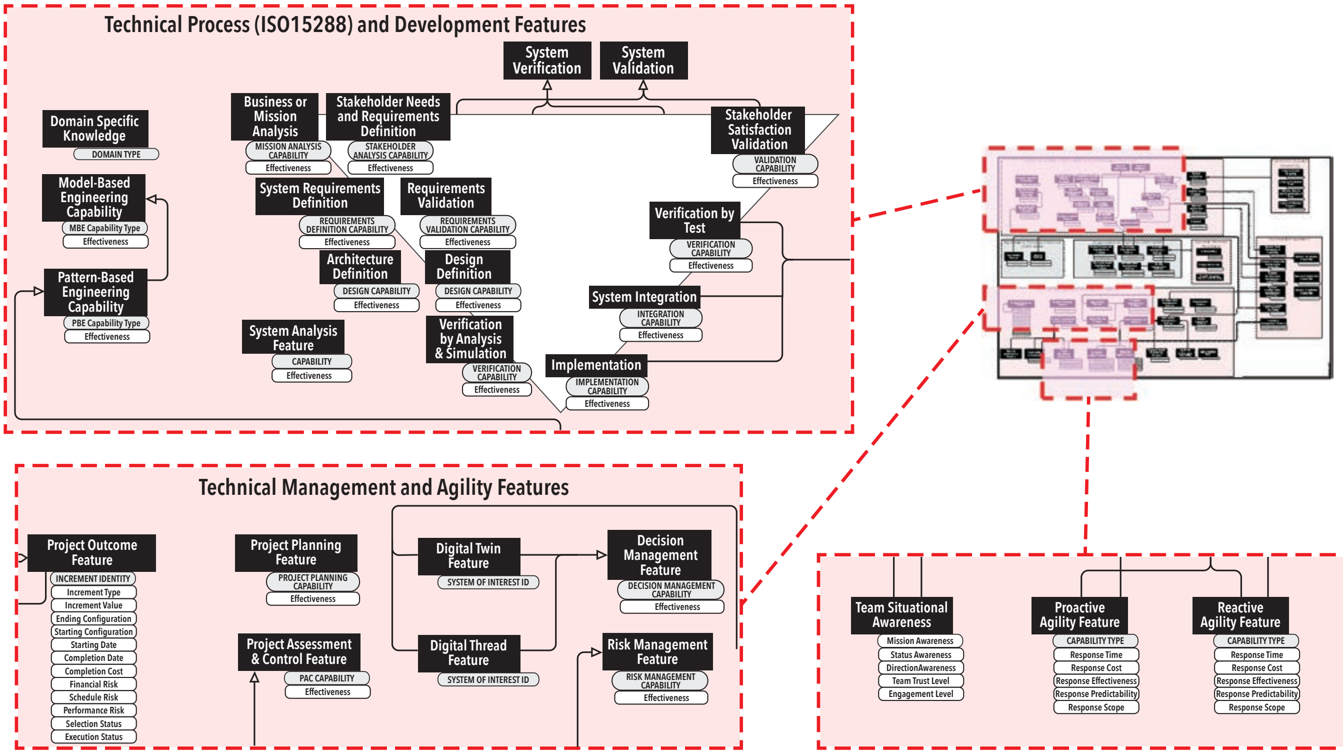


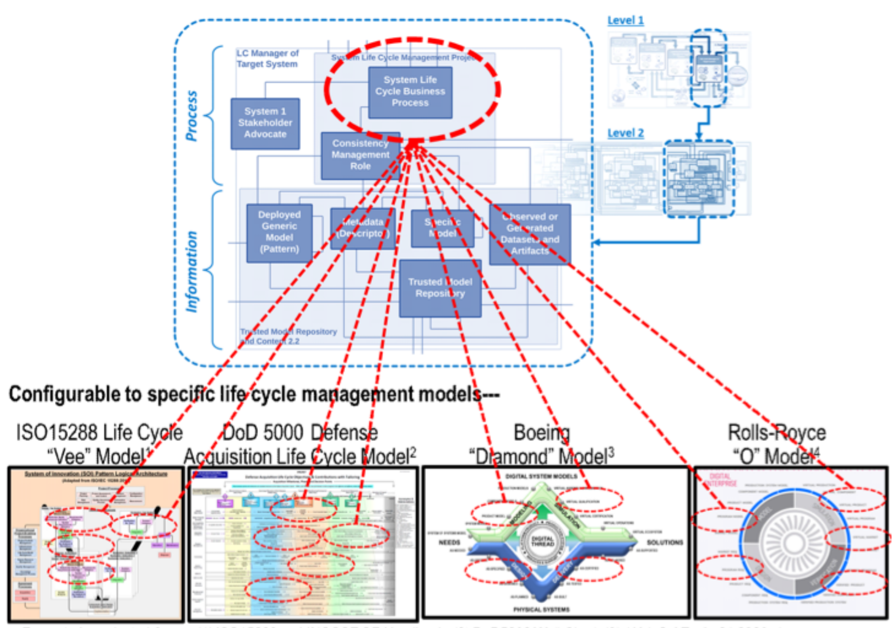
Figure 4. Configurable stakeholder features (Innovation Ecosystem System 2 Capabilities)

environment. Writing and reading this article are System 3 activities, as are many other technical society activities intended to improve the future System 2's of the world.

As an MBSE S*Pattern (a reusable, configurable MBSE model), the reference model has more components than just logical architecture, including stakeholder features (Figure 4) describing configurable ecosystem capabilities, functional interactions between functional roles, interfaces and systems of access, allocations to design components, attributes, and other components, mapped into OMG SysML. The details of the pattern methods of representation are beyond the scope of this ecosystem model article but described further in (Schindel and Peterson 2016), (INCOSE Patterns WG 2019b), and (Patterns WG 2020a).

Capabilities at the Ecosystem Level

Our first concern for an Innovation Ecosystem is for its capabilities. Figure 4 summarizes the modeled Stakeholder Features built into the configurable reference model. For a given current or planned ecosystem of interest, these undergo configuration by variably populating them (multiply in some cases) or depopulating them, and setting their attribute values, similarly to viewing the Innovation Ecosystem as a configurable Product Line Engineering model—but as a product line of ecosystems. The resulting configured feature model represents the overall capabilities of an innovation ecosystem of interest—whether past, current, or future, whether favorable or unfavorable, for analysis, planning, communication, or other purposes. A series of these configurations represents a planned or real trajectory of capabilities evolution over time. Figure 4 shows sample capabilities (features and their attributes) from ISO15288 systems engineering, along with agile engineering capabilities, digital threads and twins, and other capabilities at a stakeholder level. The feature attributes (properties) shown include Feature Primary Key attributes



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

Figure 5. Business processes of the ecosystem appear in the configurable reference model

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whose configured values invoke modeled population of specific ecosystem interactions of the roles from Figure 3, providing technical behaviors delivering the configured capabilities.

Connecting historically understood business processes to evolving digital infrastructure

The System Life Cycle Business Processes shown in the upper sections of Figures 3 and 5 represent either traditional or evolving business processes from the ecosystem (supply chain partners, enterprises, and more) description of existing or planned business processes for research, engineering, production, distribution, sustainment, and other life cycle management processes. It is these processes (typically some targeted subset of them) that the Digital Engineering enhancements shown in other blocks are to advance, as discussed in the following sections. The important point here is that the advanced digital engineering roles to be discussed next are by this means connected to the more familiar existing, traditional, or planned local reference business process framework they are to serve and enhance. We are now ready to connect those business processes to the digital engineering promise, using the key insight of the Consistency Management role introduced in Figure 3.

Consistency Management's connection to realizing the promise of digital engineering

The traditional systems engineering "Vee diagram" in the lower left of Figure 5, along with the other adjacent US DoD and enterprise models, all remind us that all engineering methods in one way or another inherently manage a series of "gaps" into acceptable "consistencies":

- Consistency of system requirements with stakeholder needs
- Consistency of system designs with system requirements
- Consistency of virtual simulations with empirical measurements (model VVUQ)
- Consistency of system component production with system design
- Consistency of system performance with system requirements
- Consistency of system operation with system requirements and design
- Consistency of system sustainment with system requirements and design
- Consistencies of many aspects with applicable technical standards, regulation, and law
- Consistencies of many aspects with learned experiences, formal patterns of requirements and design, physical science, product line rules, architectural frameworks, shared ontologies, domain specific languages, and model semantics
- Managed consistencies of the Digital Thread and Digital Twin
- Many other types of consistencies

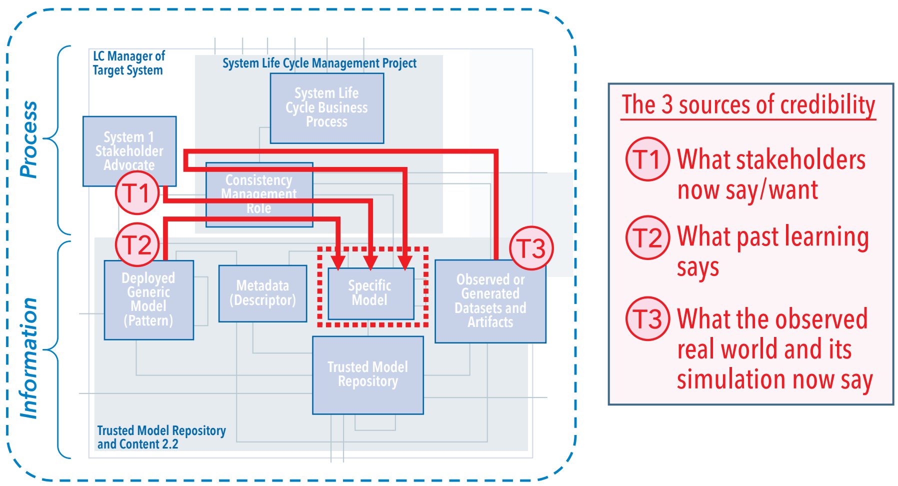

Figure 6. Roots of the consistency management challenge

The majority of the above consistencies were also a requirement in the traditional, more "tolerant" human-performed ecosystems lacking as much digital technology, even if not recognized as so.

The Consistency Management Role in Figure 3 represents the configurable set of process roles responsible for that consistency management—whether performed by humans or automated, and whether effectively performed or not. It is understandable that humans historically performed much of this role because of the required skills, judgement, and experience.

The digital engineering and modeling community finds itself in frequent conversations about a perceived need for a "single source of truth" or "authority", reflecting frustrations with diverse and inconsistent information about systems. Figure 6 reminds us that this situation is not as simple as one might assume, showing the three main sources of information in any ecosystem:

1. What the stakeholders say (market and sponsor truths).
2. What experience says (accumulated, hard-won past discoveries, physical science).
3. What empirical observation says (scientific experiment, observation, measurement).

The challenge is that these three sources will frequently be inconsistent (disagree with each other). The Figure 3 Consistency Management Roles of engineering and other life cycle management processes historically must recognize those inconsistencies and reconcile them.

The rise of interest in digital thread and digital twin methods fit into this consistency management perspective. A series of industry studies of digital twins and digital threads by AIAA is currently applying it with INCOSE support. In the case of the digital twin, it reminds us of the importance of (1) managing both consistency between the virtual simulation model and the real system it simulates, and (2) managing the consistency of business processes and their information with what the trusted digital twin virtual model tells them. In the case of the digital thread, the central issue of the "thread" is managed consistency between a range of information objects along that thread. The historical predecessors to the digital thread bring important perspective to this evolution. Depending on industry domain, these include (SAE 2016), (AIAG 2006), (ISO 2016).

Because consistency gaps are often rooted in conflicting interests of different parties, the Consistency Management role is the potential site for impactful multi-party collaboration across the ecosystem or supply chain. Enabling this collaboration with explicit models of the respective parties' collaboration configuration spaces makes it easier to understand it as a problem of differential or modular games (Schindel and Seidman 2021), (Schindel 2021), (Leitmann 1975).

Many benefits sought through transformation to Digital Engineering have been discussed widely, such as basic issues of improved information accessibility, early virtual verification through simulation, and other gains. The Innovation Ecosystem Pattern reminds us, through the Consistency Management Role, of the wider promise that a variety of Consistency Management issues at the heart of every life cycle stage may ultimately be attacked more effectively through the aid of digital information technologies that assist in Consistency Management. These include semantic web technologies, machine learning, consistency thread signatures, configurable patterns, and pattern-based model metadata. (Herzig and Paredis 2014), (Herzig, Qamar and Paredis 2014), (Kerstetter and Woodham 2014), (Redman, 2014), (Patterns WG 2020b).

Effectiveness of distributed, multi-level, group learning across an ecosystem

The promise of digital engineering should not be to optimize single program outcomes while "forgetting" learnings when the next program starts, nor to arbitrarily isolate one team's learning from other teams within a shared community. Traditional descriptions of the systems engineering life cycle processes (ISO 2015) (Walden et al 2015) describe at length all the processes a program should follow to generate all the information needed across the life cycle, but are by comparison relatively silent on the questions: "What about what we already know?" and "What about the impact on future programs of what we learned the hard way on past programs?" (We suggest that the practice of "lessons learned reports" leaves room for improvement.) The management of balancing acquisition and validation of new information versus exploiting existing information is frequently omitted in those descriptions, left for separate consideration. This is in ironic contrast to one of the great successes of modern signal processing and control theory—the optimal mixing of past experience with new information, in the presence of uncertainty, discussed further in a later section below.

The Innovation Ecosystem model views effective learning as not just accumulation of information as IP assets, but instead as improvement of future performance across the ecosystem based on experience. This especially includes more effective application of learned results that were acquired by different people at different times. The Ecosystem Pattern makes explicit the two roles of learning and subsequent application, and their integration—refer to Figure 2. That integration can include starting new program executions by configuring general learned System 1 and 2 patterns in a form specific to the new program. The MBSE Patterns Working Group refers to this capability as "pattern-based systems engineering" (PBSE) (Patterns WG 2020a).

Key System 2 capabilities that, if present, contribute to that performance include:

1. **Synthesizing Generalization:** Distillation of learning as model-based abstractions, curated at the abstraction hierarchy level where they can have the greatest future impact. The "up" (Learn) arrows of Figure 2.
2. **Validation for Context of Use:** Reusable configurable model verification, validation, and uncertainty quantification, credibility assessment, establishment of pattern metadata on provenance, credibility, and intended range of use. More on this in next section.
3. **Configuring Specialization:** Harvesting of accumulated learned patterns at time place and time they are impactful, through their configuration into new projects as part of the initiation of those projects. The "down" (Apply) arrows of Figure 2.

After we understand that configuration space is not "flat," but organized by evolving patterns at different abstraction levels, we can better understand two challenging opportunities:

A. **The dynamic evolutionary nature of semantic interoperability:** Domain-specific ontologies will continue to spring up as long as new system interactions and interaction levels are pursued describing new phenomena—and this is forever. One of the competencies required of the digital ecosystem is continuous collaborative synthesis of new, often higher-level, semantic frameworks for interoperability (Schindel 2020).

B. **The opportunities for sharing and ownership at different levels:** Shared frameworks across large ecosystems can lift the fortunes of all boats, as in the case of pre-competitive standards shared by competitors—but can be perceived as counter to the interests of individual suppliers or customers who wish to own, control, or be differentiated by less shared models. A non-flat pattern hierarchy allows for mixing of shared ecosystem-wide generic patterns with compatible specializations that competitive ecosystem members control or license. This provides for differentiation and compatibility at the same time.

Addressing the above challenging opportunties, Digital Engineering offers special promise that future ecosystems will increasingly use new information technologies that empower virtual models, their generalization and configuration, and related processes with capacity exceeding human performance alone. But it also demands new human skills and process orchestration on the human side of the Digital Engineering partnership. Model-based group learning is related to issues of trust in model credibility, discussed next.

Managed group trust in the credibility of models

Model credibility involves the verification and validation of a model's fitness for use for a stated purpose (ASME 2018), explicit tracking of related uncertainties (NAE 2012), and larger issues of propagation of trust (Rhodes 2018). The growing proliferation of model instances, types, and uses means that more uniform model metadata approaches are becoming important to describe those diverse assets in more uniform ways—somewhat like the emergence of bar code labels on supermarket products. Because there are a variety of model credibility factors that may apply, Credibility Assessment Frameworks (CAFs) can serve a useful purpose as part of that model metadata. (Kaizer 2018) The INCOSE MBSE Patterns Working Group has developed a Model Characterization Pattern (MCP) descriptive of models of all types (Patterns WG 2019a) that builds in provisions for enterprise-configured CAFs.

Many aspects of the engineering cycle are concerned with determining whether aspects of related information are worthy of trust for use in a given context. When this interest translates to operate with virtual models, the powerful technical toolset developed over the long history of the (model-based) scientific revolution bolsters it, in which the credibility of candidate models, and their repeated uses across different instances are both central. Computational model verification, validation, and uncertainty quantification (VVUQ) is a portion of this infrastructure.

Group trust in model credibility is not just a technical matter of the fidelity of the models themselves. Group trust is a socially transmitted property, in which additional credibility factors such as trust in intermediate messengers and interpreters carries great weight (Rhodes 2018). Models of how credibility (or doubts of credibility) propagates through ecosystems can illustrate the contest of multiple factors impacting group trust, distrust, confidence, or doubt. The above Credibility Assessment Frameworks (CAFs) preserve for future reference the basis on which past groups awarded credibility to a given model.

Managing the proliferation of model diversity and instances

Such model credibility information is a special case of larger class of model metadata—information outside a virtual model that describes the virtual model. Model metadata can variously include description of a model's focal subject, structure, algorithms, intended model use and context of that use, model provenance, model credibility, the nature and scope of the virtual model, and refer to related model artifacts, datasets, and life cycle maintenance history. Figure 3 graphically notes the role that model metadata plays within the innovation ecosystem, describing diverse virtual models to their potential users, as a kind of uniform "labeling wrapper" of evolving virtual models. While it has been common to consider many aspects of information technology in planning DE, awareness of the broader roles of virtual model metadata deserves expanded awareness.

The diversity of types of virtual models includes at least computational models (simulations of all kinds) and descriptive MBSE models but can also include other forms of formalized standards-based data structures. Simulations alone may include physics-based FEA and CFD discretized continuum simulations, ordinary differential equation-based simulations, machine learning models and other forms of data-driven models, and others. Adding to this diversity are varied styles, computing environments, and methodologies for model verification, validation, uncertainty quantification, and credibility management. Increasing separation between model authors and model users exacerbates the problems resulting from this explosion of model diversity as well as model quantities.

The Model Wrapper generic metadata role shown in Figure 3 serves purposes analogous to the package labeling, inserts, and supplemental downloads common to consumer products. Imagine walking into a modern supermarket, big box store, or distributor web site, and finding that all the package and shelf labeling and explanations have disappeared except for the ability to directly view the products (remember earlier open-air market bazars). This conveys some idea of the current situation concerning proliferation of thousands of models within an enterprise, and even more pronounced across a multi-enterprise ecosystem in which exchange of models occurs.

Generic metadata frameworks for engineering models, such as the Model Characterization Pattern (Patterns WG 2019a) and Model Identity Card (MIC) (Goknur 2015) are key enablers to the effectiveness of the digital engineering in the Innovation Ecosystem.

Effective evolution of the ecosystem itself

Among the promises of the DE ecosystem are its own adaptability, as future environments and market situations may demand. An essential capability described by the Innovation Ecosystem Pattern is that adaptability. In Figures 1 and 2, System 3 is concerned with the adaptability of System 2, beginning by observing and representing it, followed by analyzing and deploying adaptations to System 2 instances. The deployed or updated "design components" of System 2 are the collaborating people, enterprises, information systems, equipment, and facilities of System 2, accompanied by their organization, planned over agile release train configurations of the System 2 pattern. In addition to the challenges of engineering, this adaptation also carries all the challenges of enterprise organizational change management (OCM) (Kotter 2014). Just as the forces of multi-stage selection operate over the life cycles of the engineered products of System 1, (other) multi-stage selection forces also shape the evolution of System 2 (Patterns WG 2029). Understanding those forces is essential to the conscious design of (or at least influence on) the evolution of System 2. For complex business ecosystems involving multiple partners, not only is the alignment of their technical capabilities vital, but also the alignment of their business interests and incentives. These issues should remind us that successful collaboration across System 2 requires more than just a digital medium for that collaboration.

In the language of business management community, "business ecosystem" has come to refer to particular ecosystem architectures (for System 2) which operate flexibly as small "markets" in which modularity of the System 1 technical approach encourages a more dynamic (and accordingly less stable) arrival and departure of competing candidate System 2 partners offering contributions to solutions. (Jacobides et al 2017)—this in contrast to traditional OEM plus captive smaller suppliers linear supply chain network models. One can see both the advantages and disadvantages of such approaches in the history of the personal computer (PC). Early PCs were proprietary closed architectures from competing end product suppliers. IBM disrupted this picture when it opened the digital product's electronic circuit card bus specification and business ecosystem to third party suppliers who could directly supply add-in circuit cards to the end user. The market dramatically expanded through innovative add-ons, lifting all boats, but eventually driving the originator (IBM) of that approach out of the market. These are not just stories of the System 1 architecture, but also of the System 2 architecture.

We can understand selection processes performed by System 2 and 3 as cycles of their Consistency Management Roles (see Figure 3), selecting opportunities, requirements, candidate designs, and other aspects of both System 1 products and System 2 enterprise designs. In those cycles, Digital Engineering offers special promise for exploiting the following "Goldilocks" insight from the successful history of engineering certain challenging systems:

1. **More consideration of empirical inputs:** When stakeholders needed more supplier agility to converge sooner on their real needs with real solutions, the pioneers of agile engineering introduced cycles that generated and paid earlier, more frequent, and ongoing attention to incoming reality signals from System 2 experiment and empirical measurements involving real world signals instead of isolated planning. The upside of this produces early minimum viable products (MVPs), rapid learning by individuals and small teams, and successful "pivots." On the downside, it may miss exploitation of previous discoveries and can produce ill-conceived course changes chasing noisy data.
2. **More consideration of patterns of experience:** When more instances of variant products proliferated to address different market segments, the pioneers of design patterns and product line engineering introduced cycles that paid more attention to shared historical patterns of product designs, requirements, and other common but configurable assets. The upside of this produces increased IP leverage and flexibility. If overperformed, it risks constraints that may miss external shifts and trends, dragging along too much of the past.
3. **Goldilocks as Kalman: More optimal mixing observation and experience:** Formal systems engineering process descriptions often tell us all the things we should do to learn what is needed for good life cycles, but may be silent on the questions "what about what we already know?", and "how can we discover new things sooner?", addressed by the two complementary points of (1) and (2) above. In one of the most impactful examples of breakthrough engineering through applied mathematics, Rudolf Kalman introduced an approach to optimal mixing of these two in the presence of uncertainty, the Kalman Filter approach to Bayesian estimation, power navigation to landing on the Moon, world-wide personal

communication systems, countless industrial control systems, and other applications of this combination. Digital Engineering offers a medium in which the Consistency Management Role of Figure 3 can advance to better leverage those applied mathematics insights in support of human decision-making (Schindel 2017b). Improving ontological patterns can improve meaning and understanding of empirical data from improved sensory and observational networks. Collaborative ecosystem efforts to create capabilities such as JADC2 can benefit from these historical insights. (CRS 2021).

NEXT STEPS—AN INVITATION

The systems engineering community has a shared interest in the network benefits of community-wide advancement of the ecosystem for digital engineering. The INCOSE MBSE Patterns Working Group continues to pursue the discovery and expression of explicit model-based patterns, which fuel digital ecosystems as "water through their pipes," but which also represent those ecosystems themselves (Patterns WG 2021).

The Patterns Working Group conducts most activities as collaborations with other INCOSE and additional technical society groups, to advance awareness and the state of practice. We invite interested readers to participate in this progress and learn along with us about:

- Details of the Ecosystem Pattern, now being tested in its OMG SysML form
- The Ecosystem Pattern as a digital engineering capability planning aid (Patterns WG 2020c)
- Basics of S*Models, S*Patterns, and the S*Metamodel (Patterns WG 2019b)
- Domain specific applications of model-based patterns (Patterns WG 2021) ■

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Digital Twin: Reference Model, Realizations, and Recommendations

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■ **ABSTRACT**

Organizations continuously develop Digital Twins across a wide number of applications and industries. While this represents a testimony to the benefits and opportunities Digital Twins provide (AIAA 2022), their development, maintenance and evolution still face major challenges (Bordeleau et al. 2020). 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 (Martin 2019, Lu et al. 2020). 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 (Martin 2019)]. The development and implementation of Digital Twins also lack standardization (Shao 2021), instead relying on bespoke methods and technologies (Niederer et al. 2021), which in turns leads to a lack of consistency in their description and implementation, as well as limited interoperability across applications, tools and disciplines (Niederer et al. 2021, Piroumian 2021). 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 (Niederer et al. 2021).

The development of standardized methodologies has been identified as a means to unleash the full potential of Digital Twins (Shao 2021, Piroumian 2021) and increase their adoption across a wider range of disciplines and applications (Niederer et al. 2021). 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. It also introduces real-world examples of aerospace Digital Twin use cases and discusses how the generic reference model supports the various use case applications. Finally, this paper briefly discusses recommendations and next steps on how to realize value from Digital Twins more broadly.

■ **KEYWORDS:** digital twin, digital engineering, ASELCM, generic reference model

1 DESCRIPTIVE REFERENCE MODEL FOR DIGITAL TWINS

This paper configures the ASELCM reference model, presented in the previous INCOSE INSIGHT article, to describe real-world examples of aerospace Digital Twin use cases provided by an AIAA industry and academic team. This article also provides common views on how the generic reference model supports the various use case applications. Finally, this article provides recommendations for a coordinating body to help secure and further benefits, and later discusses next steps on how to realize value from Digital Twins more broadly.

The reference model chosen 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, and was used in an award-winning study series of INCOSE publications to improve understanding of patterns of ecosystem agility in a systems engineering context (Schindel and Dove 2016; Dove, Schindel, and Scrapper 2016; Dove and Schindel 2017; Dove, Schindel, and Hartney 2017; Dove, Schindel, and Garlington 2018). Another AIAA position paper, currently going through peer-reviews, to describe the broader Digital Thread uses the same reference model. The ASELCM Pattern addresses the set of system life cycle management challenges inherent to innovation and engineering of systems, as described in (INCOSE 2014) and (ISO 2015).

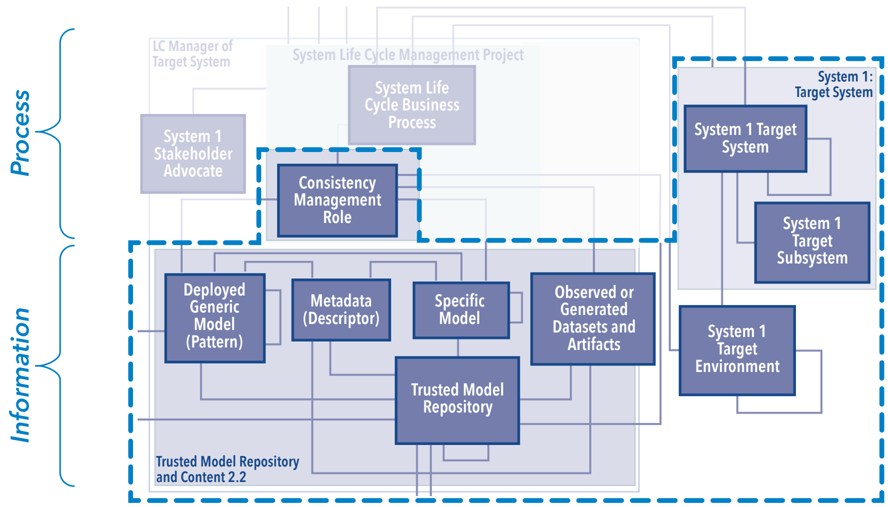

Figure 1. Managed digital twin system boundary

A full description of the ASELCM Pattern is discussed in the earlier article of this INSIGHT edition entitled "Realizing the Value Promise of Digital Engineering: Planning, Implementing, and Evolving the Ecosystem." As described in the earlier article, and of particular importance to understanding disparate Digital Twins, is consistency management as a paradigm for Digital Twin's contribution to Engineering and Life Cycle Management. By illustrating the system boundary of the Managed Digital Twin, Figure 1 summarizes the emphasis on the credibility of the Digital Twin simulation, and other forms of Consistency Management across the Digital Thread in general.

2 SUMMARY OF REALIZATION CASE STUDIES

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. Digital Twins predict mission operations and vehicle performance with actual performance during a mission updating future predictions.

From an ASELCM 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 ASELCM System 2 features therefore extend to include Mission Planning, along with Requirements Definition, Digital Twin Feature, and Decision Making (Hutchinson 2017; Huchinson and Bocam 2009; https://www.northropgrumman.com/space/cygnus-spacecraft/).

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. To achieve this objective users will link material models, structural models, and experiments at multiple length scales. This aeronautical relevant benchmark problem serves to demonstrate the benefits of an Integrated Computational Materials Engineering (ICME) approach. Digital representative models will generate at every scale, with some or all rising to the level of twin(s) depending upon consistency with scale specific measures of merit. With respect to the ASELCM reference pattern, this digital twin study is active in both System 2 (where teams generate and use models of the different scales) and System 3 (where teams use models to describe, deploy, and study new paradigms of the System 2 work processes). 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

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 users develop 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 (Sisson, Karve, and Mahadevan 2021).

From an ASELCM 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

Digital twins can enable more accurate and timely modeling of manufacturing results. Modeling digital twins during manufacturing is challenging because the processes one must measure developed over many years. Adding digital twins is only beneficial if organizations can achieve further savings without reducing quality or slowing production. In the summer of 2020, the AIAA industry and academic team implemented three case studies to validate the digital twin framework. They developed all three test cases to show how digital twinning can make manufacturing more flexible and accurate (ISO 2021).

Viewed from the perspective of the generic ASELCM reference model, System 1 represents the manufactured product and System 2 the product engineering and manufacturing system, the current use case focuses on System 3, where the digital twin and manufacturing engineering system exists. 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, and more), therefore include Consistency Management, the Configured System Model, Empirical Datasets, Descriptive Model Metadata, accumulated simulation Patterns, and the Trusted Model Repository.

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 certification testing historically assured seat structural integrity and occupant safety, models can achieve the same level of passenger safety by analytical methods due to recent advancement of "Digital Twin" computer modeling and simulation technology. The airplane seat digital twin utilized simulation of seats as a means of regulator (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) (Boeing Commercial Airplanes 2017). The development of the digital twin of the airplane seat and its implementation focused on safety (SAE 2012) 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.

From an ASELCM 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 ASELCM System 2 features extend to include Stakeholder needs and requirements analysis, along with Implementation, Verification by analysis and simulation, MBE capability, and Acquisition.

Georgia Tech's Kendeda Building Digital Twin

The Aerospace Systems Design Laboratory (ASDL) at Georgia Tech (GT) in support of GT's Kendeda Building for Innovative Sustainable Design (KBISD) created a Digital Twin. The 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) (Post 2021). The Digital Twin needed to experience the to the same conditions—weather, occupancy, control schemes—as its real counterpart to serve as a baseline for quickly detecting faults that would jeopardize certification. During the 12-month certification period, use of the Digital Twin also enabled GT to forecast the net "budget" of water and energy through remaining months to gage whether the building might be "programmed" (planned) for more intensive use by occupants and visitors.

With respect to the ASELCM reference pattern, this digital twin study is active in both System 2 (where teams generate and use models of different scales) and System 3 (where teams use models for to describe, deploy, and study new paradigms of the System 2 work processes). 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 ASELCM systems (system 2 or 3).

3 SUMMARY OF ASELCM APPLICATIONS

The diagrams below synthesize how the generic reference model supports the various use case applications presented in the previous Section. In particular, Figure 2 through Figure 4 summarize how the use case applications fit together into the different roles necessary for any system.

In Table 1 the significant role of consistency management is highlighted for each case study. Please refer to Figure 6 of the earlier article of this INSIGHT magazine for more detailed description of the roots of consistency management. However, for the configuration of these case studies, the left two columns with shaded blocks of the Modeled System depict relevance to either system 1 or 2. Likewise, the colored in blocks for each case study correlate distinct types of managed consistencies to each case study. These correlations are important to case study success.

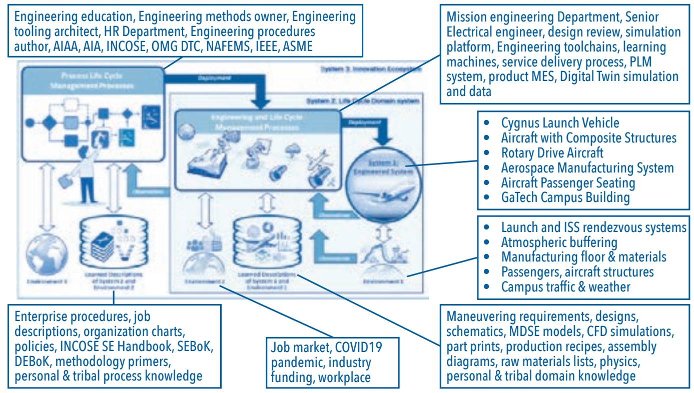

Figure 2. ASELCM logical architecture, level 0 view across the use case applications considered

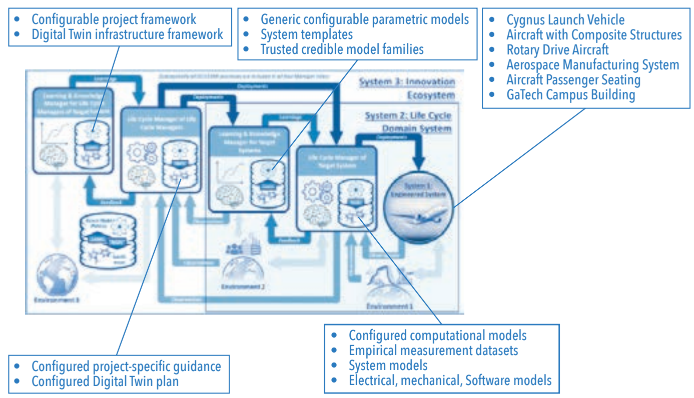

Figure 3. ASELCM logical architecture, level 1 view across the use case applications considered

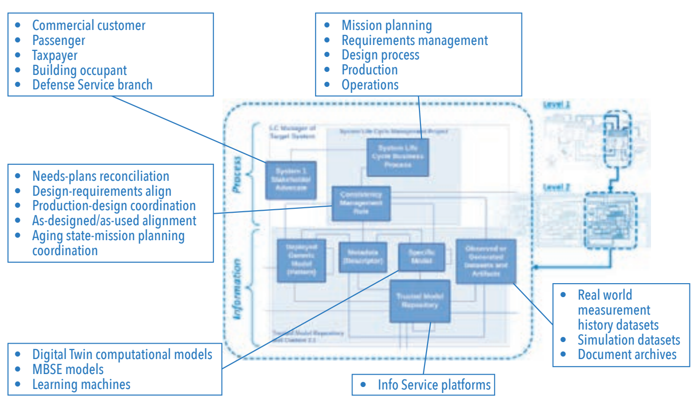

Figure 4. ASELCM logical architecture, level 2 view across the use case applications considered

4 RECOMMENDATIONS

This document has presented configurations of a generic reference model for describing how Digital Twins integrate with the broader digital enterprise. Furthermore, this paper describes a subset of Aerospace Industry use cases and case studies which demonstrate the relevance and utility of this reference model. This work provides the needed context for collaboration and consistency management so the Aerospace Industry can move out toward realizing the greatest value from digital twin implementation.

Recommendations on ASELCM Methodology

Methodology recommendations for planning and implementing Digital Twins include:

Table 1. Consistency Management Applied to the Case Studies

	Model 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 Bldg
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 Consistency	Mission Planning: Product or Use						
5			Product Requirements and Design versus Supplier Product	Initial Acquisition and Subsequent Inspections						
6			In Service Product Maintainability versus Requirements	Improve Service Process or Product						
7			Production Consistent with Product Design Specification	Production Quality Control and Yield						
8			Production Consistent with Product Design Specification	Production Throughput, Efficiency						
9			Requirements for Digital Twin Capability, versus Twin Plans	Acquiring Digital Twin Capability						
10			Requirements for Digital Thread Capability, versus Twin Plans	Acquiring Digital Thread Capability						

- Implementing Digital Twin(s) demands enterprise level systems engineering. Understanding the benefits targeted by the Digital Twin requires understanding aspects of the enterprise system in which one Digital Twin.
- Alignment with related enterprise efforts can impact success. The current period finds aviation and aerospace enterprises mid-stream in many programs of change, and Digital Twin implementation should be considered during program planning.
- Managed trust in the ongoing fidelity of the Digital Twin for purpose and over time is essential. The Digital Twin must be a trusted source of information in a way that fits the intended application of the Digital Twin.
- 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.

Recommendations on Digital Twin Implementation Future Steps

Consistent with the recommendation from the seminal AIAA/AIA Digital Twin Position Paper (AIAA Digital Engineering Integration Committee 2020) and validated from the foundational work here, the Aerospace Industry recommends creating and/or leveraging one or more existing Aerospace Digital Transformation Consortia (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.
- **Ensure Scalability (Strategic)** – Leveraging enterprise frameworks and models, the ADTC owns development of a joint grand strategy and scalable framework to coordinate Aerospace Industry efforts toward value realization from Digital Twin implementation.
- **Promote Awareness (Marketing)** – Through liaising with existing consortiums 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.
- **Influence Policy and Regulation (Political)** – To accelerate realization from published "Digital Engineering" vision and strategy documents, an ADTC will work with Government establishing appropriate policy, regulation, and incentives for 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 offer more context on each of the above, specific activities and next steps should happen as part of a potential ADTC effort. The forthcoming Digital Twin Implementation Position Paper by AIAA DEIC explains descriptions of potential future efforts.

5 TOWARD IMPLEMENTATION OF RECOMMENDATIONS

The above recommendations highlight current gap areas 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 no one organization can deliver it, but focused enough to allow Industry alignment around the problem. Industry has identified **Joint All Domain Command & Control (JADC2)** as an ideal candidate to take forward as an initial grand challenge or "North Star" effort. 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 (Zadalis 2021). An ADTC, using a generic reference model, will enable joint C2 for a common mission thread to demonstrate digitally. 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. An ADTC can help provide focus and influence a resulting roadmap to accelerate benefit realization from joint C2 in an appropriately phased approach.

6 CONCLUDING REMARKS

Individual organizations are realizing targeted benefits from Digital Twins and Digital Engineering capability. Broader 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. ■

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Versatile Test Reactor Open Digital Engineering Ecosystem

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■ **ABSTRACT**
Modern design of nuclear facilities represents unique challenges: enabling the design of complex advanced concepts, supporting geographically dispersed teams, and supporting first-of-a-kind system development. Errors made early in design can introduce silent errors. These errors can cascade causing unknown risk of complex engineering programs. The Versatile Test Reactor (VTR) Program uses digital-engineering principles for design, procurement, construction, and operation to reduce risk and improve efficiencies. Digital engineering is an integrated, model-based approach which connects proven digital tools such as building information management (BIM), project controls, and systems-engineering software tools into a cohesive environment.

The VTR team hypothesizes using these principals can lead to similar risk and cost reductions and schedule efficiencies observed in other engineering industries. This research investigates the use of a digital engineering ecosystem in the design of a 300-MWt sodium-cooled fast reactor. This ecosystem was deployed to over 200 engineers and used to deliver the conceptual design of the VTR. We conclude that initial results show significant reductions in user latency (1000x at peak use), the possibility of direct finite-element-analysis (FEA) integrations to computer-aided design (CAD) tools, and nuclear reactor system design descriptions (SDDs) that we can fully link throughout design in data-driven requirements-management software. These early results led to the VTR maintaining milestone performance during the COVID-19 pandemic.

■ **KEYWORDS:** digital engineering, digital twin, digital thread, versatile test reactor, Idaho National Laboratory

I. INTRODUCTION

The VTR program has referenced the Department of Defense (DoD) digital-engineering strategy (https://fas.org/man/eprint/digeng-2018.pdf) as a key upper-level strategy for VTR implementation. The DoD breaks digital engineering into five key functions:

1. Transform to end-to-end digital representation through models.
2. Structure information into an authoritative source-of-truth.
3. Integrate technological innovation and technology advancements.
4. Provide an information technology (IT) infrastructure and environment to support the process.
5. Change the culture and workforce through change management, communications, training, and strategy.

This digital transformation approach proved to reduce the schedule by approximately 10 years on new DoD aircraft (https://www.foxnews.com/tech/air-force-flies-6th-gen-stealth-fighter-super-fast-with-digital-engineering), increase performance by 25% in construction (https://www.mortenson.com/vdc/study), and avoid $1 billion in cost through advanced digital twins (https://www.ge.com/digital/blog/industrial-digital-twins-real-products-driving-1b-loss-avoidance). To deliver on this strategy and attempt to receive similar benefits for an advanced Gen-IV nuclear reactor, the VTR Program has decomposed this strategy into key implementation-focus areas (see Figure 1. Digital Engineering Strategy).

The VTR program has implemented each function of the DoD strategy through the following five key areas:

1. Data-Driven Tools: For data capture in design engineers deploy BIM, project portfolio management, and data systems-engineering tools.
2. Digital Thread: An open-source data model (ontological)-focused software platform to connect nuclear data.
3. Technological Innovation: Partnership with universities to provide integration with FEA and artificial intelligence/machine learning (AI/ML).

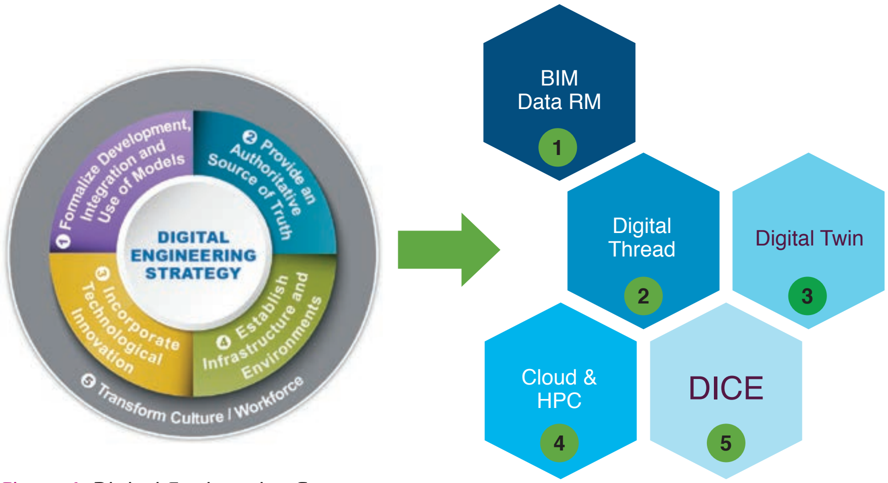

Figure 1. Digital Engineering Strategy

4. Cloud and High-Performance Computing (HPC): An environment and infrastructure to host data-driven tools throughout the VTR team.
5. Digital Innovation Center of Excellence (DICE): A community of practice to transform laboratory culture.

Idaho National Laboratory (INL) provides the tools, digital thread, and computing for the VTR program with laboratory and industry partners, contractors, and supporting universities interfacing with this environment.

II. DIGITAL ENGINEERING FUNCTIONS

Data-Driven Tools

The VTR Program uses models and data-driven tools across the engineering process to facilitate design. Currently, key tools for the program are BIM for two- and three-dimensional (2D and 3D) CAD/equipment, systems-engineering, and project portfolio-management software.

The AVEVA solution manages BIM for the capture of engineering design data. BIM has several capabilities, including the capture of 2D piping and instrumentation diagrams (P&ID) and 3D mechanical, civil, and structural diagrams. AVEVA's suite of software includes a web-based collaboration platform, AVEVA Net, to enable project stakeholders to collaborate and review digital-asset information across the lifecycle in real time. AVEVA defines a data model, with mapping to the digital thread authoritative source of truth.

The team deployed the IBM Jazz engineering life-cycle management (ELM) software for the development of systems-engineering artifacts. The Jazz ELM includes a suite of integrated tools to manage requirements, define test cases (through verification and validation), model physical and logical architectures, and manage system changes. These tools are web-based and require no software installation on client machines. The Jazz ELM uses an open standard—open services for life-cycle collaboration (OSLC)—to enable links across the systems-engineering tool suite. These links enable a named association (satisfied by) between systems-engineering artifacts, to currently 5225 requirements artifacts are currently allocated, including all system-level requirements. This allows connection within the Jazz software system itself. To connect to the authoritative source of truth engineers developed a software adapter and compatible ontological linkage.

The VTR Program uses the Oracle Primavera P6 enterprise project portfolio-management (EPPM) software. The P6 EPPM platform is used to develop the integrated master schedule, to integrate planned and actual costs, and to define overall project health. P6 provides a web-services application program interface (API) which the team integrated as an adapter to the authoritative source of truth.

Digital Thread

The authoritative source of truth consists of two key technologies: a database to centrally store all information across the program and a formalized data model or ontology to organize the information. VTR uses an open-architecture data framework, Deep Lynx, originally developed on the VTR to centrally integrate and store the source-of-truth data. All data in Deep Lynx map to the open-source Data Integration Aggregated Model and Ontology for Nuclear Deployment (DIAMOND). DIAMOND contains classes, their properties, and relationships that represent various concepts and data within the nuclear domain (Figure 2–Deep Lynx Architecture).

Deep Lynx is a data warehouse, unique in that it stores its data in a graph-like format which maps to a user-provided ontology or taxonomy. Currently, engineering teams operate in siloed tools and disparate teams, where connections across design, procurement, construction, and operating systems undergo manual translation or over brittle point-to-point integrations. The manual nature of data exchange increases the risk of silent errors in the reactor design, with each silent error cascading across the

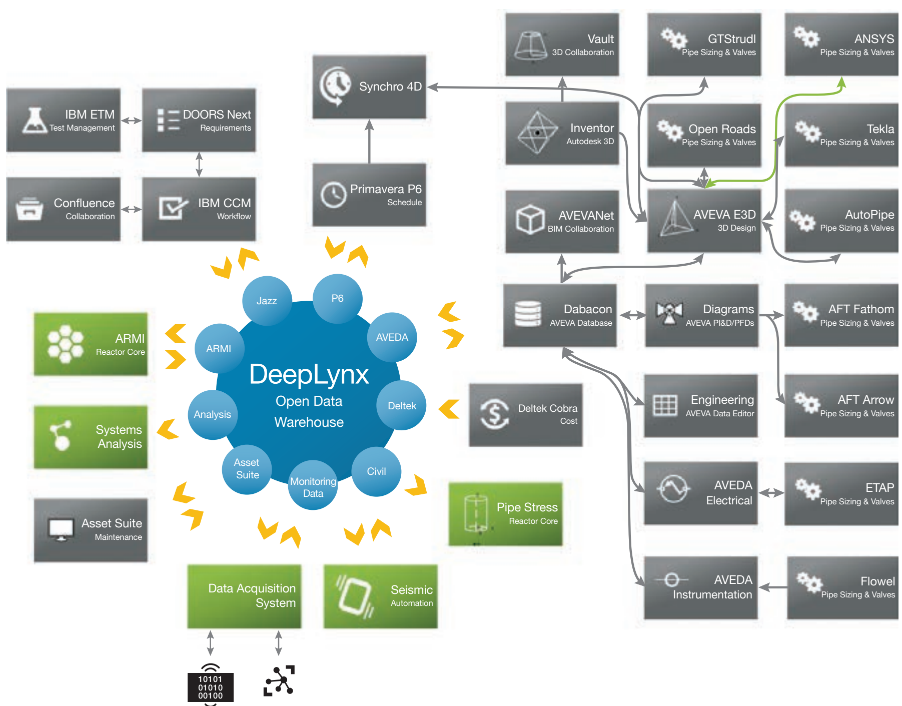

Figure 2. Deep Lynx architecture

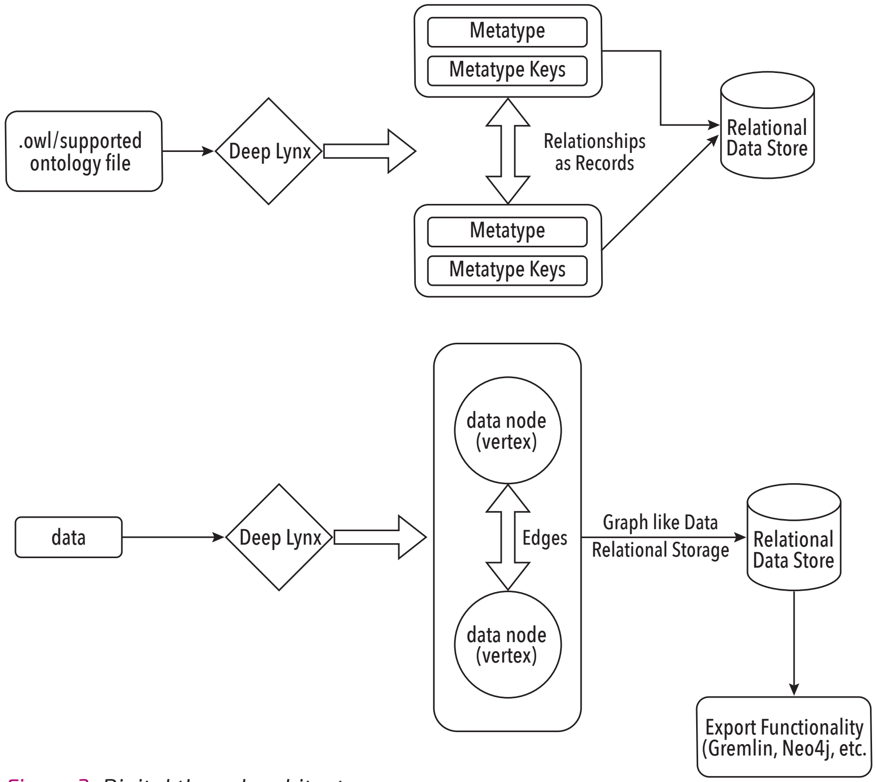

Figure 3. Digital thread architecture

design. Deep Lynx allows for an integrated platform during design and operations of megaprojects. Deep Lynx allows the user to safely and accurately aggregate data from various programs and data sources, store those data in a user-provided organization such as the DIAMOND ontology, and then generate reports and visualize ingested data.

The Deep Lynx software system can map to a provided W3C Web Ontology Language (OWL) file to instantiate a container with an ontology. A container separates between different sites or areas of work. Containers also allow Deep Lynx to manage user interaction with certain data, enforcing security controls at this level. Within a container, information from the ontology classes is persisted as metatypes for classes, metatype keys for class properties, and metatype relationships for relations between classes (see Figure 3–Digital Thread Architecture). This controls the database schema within a container. Data themselves persist as a set of nodes and vertices (edges) that map to the equivalent metatype and metatype relationship accordingly. Users can view these data can relationally, through GraphQL, or export them to view in any Gremlin-compatible graph database.

For an import's data to insert into Deep Lynx, each dataset must be associated with a Type Mapping. A type mapping defines how the incoming data maps to the defined ontology or taxonomy within Deep Lynx. Type mappings apply constantly to matching data automatically and require no user intervention apart from teaching the system through creation of new type mappings when there are new data structures submitted. Once an import's data completes mapping, the transformation and insertion process will begin automatically.

Technological Innovation

Managing design changes during construction for a nuclear energy facility requires the involvement of multiple design engineers to effectively communicate and collaborate changes that branch from a new change. To provide effective management and streamlined communication of design changes, engineers develop an automated bi-directional conversion of facility structure and piping systems. This interoperability solution between building information models (BIM—for example: Autodesk Revit, AVEVA E3D, and more) and physics-based model (i.e., finite-element model in advanced modeling and simulation [M&S] tools, such as ANSYS or Abaqus) allows quick conversion of as-built BIM models into analytical models. Any design changes during construction— hanger support location for a piping system due to site constraint—can reflect or show in an analytic model for quick assessment of risk. On the other hand, any new changes by designers in the analytical model— an increased number of hanger supports for the piping system—can be quickly translated into the drafting model (BIM) that the contractor use for construction. The process diagram in Figure 4–Versioning of design changes through bi-directional conversion of BIM and M&S models illustrates this quick assessment through bi-directional BIM-to-M&S conversion and its integration with Deep Lynx for versioning of design changes.

Deep Lynx, as a data warehouse, stores these BIM and analytical models and their versioning information through a simple relational database/structured query language (SQL), allowing pulling and pushing of the latest design changes. It can also allow tracking of changes by querying models at different times. The versioning as part of Deep Lynx has a synergistic opportunity for better managing building information

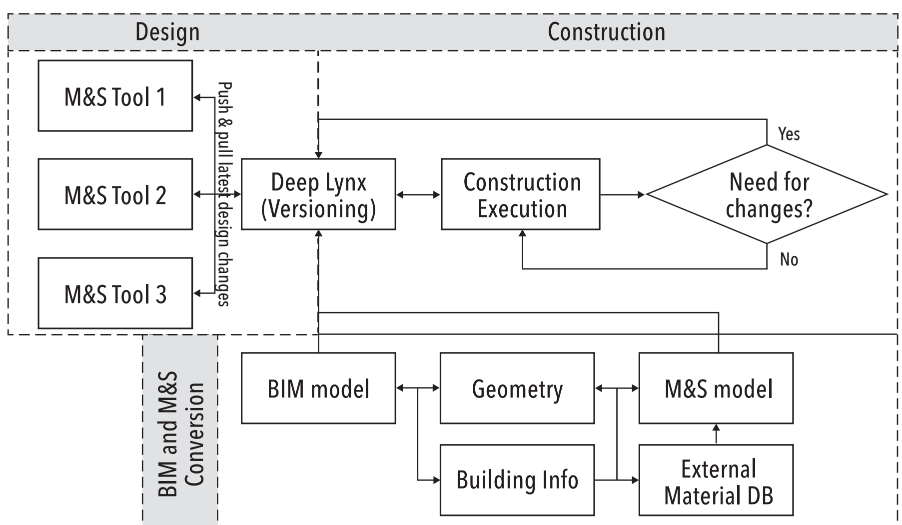

Figure 4. Versioning of design changes through bi-directional conversion of BIM and M&S models

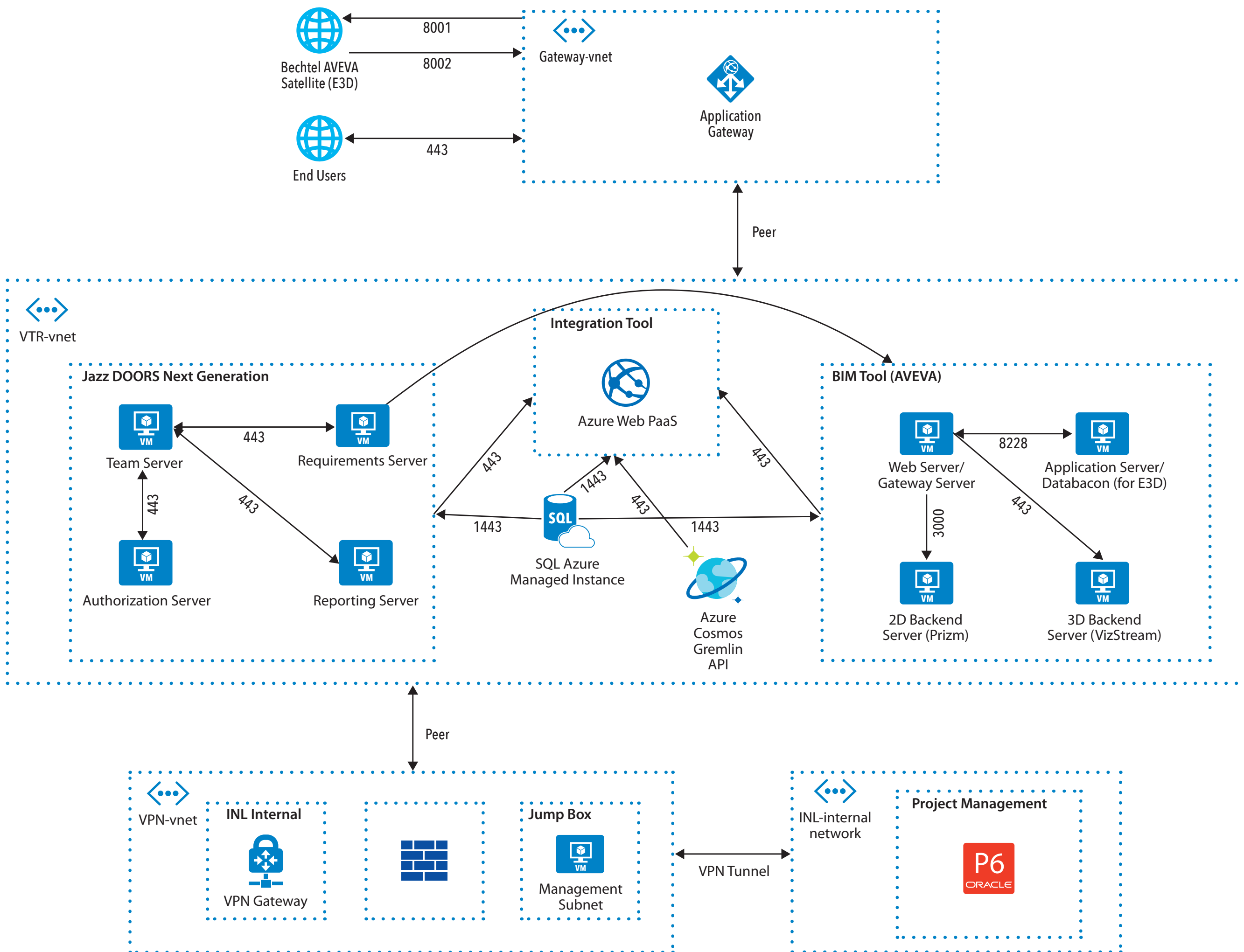

Figure 5. VTR network diagram

throughout the design and construction phases. It can function as a central data hub for accessing design and construction models at different times for accurate access of information, minimizing the accumulation of human errors while managing the ever-increasing list of design changes. Last, keeping the most up-to-date building information through construction would be beneficial for the operational phase, especially given the digital-twin concept of operational monitoring and simulation.

Cloud and HPC

The Microsoft Azure for Government Cloud hosts the VTR digital-engineering software tools and ecosystems . The U.S. Department of Energy (DOE), Idaho Operations Office (ID) approved this cloud to host data up to official use only (OUO)/ export-controlled information (ECI).

The INL-managed cloud environment uses virtual networks to contain and separate different programs. The architecture includes a hub virtual network (VNET) which connects to the VTR internal spoke VNET. This hub VNET is then peered to an external spoke, which is peered to the internet. The INL Information Management networking teams manage configuration of this network; changes to the VTR spoke must receive approval though a change-request board.

An overview of the current VTR digital engineering network architecture follows as Figure 5 - VTR Network Diagram:

This environment dramatically reduced peak latency of the requirements-management tool, Dynamic Object-Oriented Requirements System—Next Generations (DOORS-NG), during peak use. Latency between the database server and application was 3,000 ms during peak times before cloud migration, with latency reduced to 2–3 ms duration once cloud migration was complete. This represents a 1000× decrease in peak latency. Additionally, end-user latency was reduced from to approximately 6 ms to 60 ms, depending on geographic location.

An automation is in development between Deep Lynx's cloud and the INL's HPC environments. This automation uses a queue model to allow computationally expensive models (multiphysics) to send to HPC for processing but uses the cloud to distribute the results geographically among the team.

DICE: Culture and Workforce Transformation

DICE serves as a virtual center to formalize and coordinate digital-engineering, digital-twinning, and digital-transformation activities across next-generation energy systems (https://dice.inl.gov). DICE is a laboratory-wide service that provides to leadership a strategy focused on energy-system needs, recognition through research accomplishments, coordination to share community best practices across the laboratory, outreach to universities, industry partners, and other national laboratories, and enhancement training and education materials on digital engineering and twinning. The VTR shares best practices with the DICE community and encourages process transformation to support digital engineering.

III. CONCLUSION

The digital-engineering strategy implemented for the VTR program led to sustained milestone performance throughout the COVID-19 pandemic. The ecosystem of digital tools allowed for contractors, laboratories, and universities to seamlessly switch to digital collaboration as the primary means of communication. To date, this strategy led to all system-level requirements to be persisted at the object level, latency reduced by 1000× during peak use, and proof of CAD-to-FEA integration automation. Additionally, changes to any of the more than 5000 requirements are automatically tracked and updated across the program, ensuring that potential silent errors are avoided. The VTR program's technologies have seen expanded use on other DOE nuclear-reactor programs, National Nuclear Security Administration (NNSA)-safeguards digital twins, and commercial nuclear programs. As the VTR program matures planned continued expansion of the Deep Lynx ecosystem and automation will realize cost reductions, schedule improvements, and engineering performance gains. ■

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Lee Nelson is the director of acquisition and logistics on the VTR Program. Lee has over 30 years' experience in project engineering, project management, and chemical engineering. On the VTR, Lee established the digital engineering sub-project and currently advises on all aspects of practical engineering application. Recently, Lee served as the project engineer on the DOE TREAT program which delivered a year ahead of schedule and $20 million under budget.

John Darrington is a digital twin research scientist working in the digital engineering department at INL. Specializing in software engineering and design, John continuously works to introduce and manage new technology and strategies in the digital engineering world. John has worked with the digital engineering department for the last 3 years and most recently has spearheaded efforts on an internal data warehouse, Deep Lynx.

AnnMarie currently works as the management of configuration management in support the VTR program at INL. She participated in authoring and submitting their critical decision (CD) documentation and establishing and managing their CM Program. In addition, AnnMarie established, created, and managed VTR the project records repository. Prior to working at BEA, AnnMarie was the Manager for Configuration Management for New Plant Projects at GE-Hitachi Nuclear Energy (GEH) where she participated in multiple projects related to the ESBWR, ABWR, and PRISM product lines.

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Digital Engineering Measures Correlated to Digital Engineering Lessons Learned from Systems Engineering Transformation Pilot

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ABSTRACT
This paper discusses analysis that correlates Digital Engineering Success Measure (DESM) categories with lessons learned benefits observed during the NAVAIR Surrogate Pilot that applied Digital Engineering (DE) methods and tools using an Authoritative Source of Truth by modeling everything to demonstrate the art-of-the-possible. The analysis correlated rating from seventeen lesson learned categories to 22 DESMs grouped into four metrics categories.

KEYWORDS: digital engineering; authoritative source of truth; model-based systems engineering; measures; metrics; digital engineering success measure

1. INTRODUCTION

The Department of Defense (DoD) has initiatives to transform DoD acquisition processes from the current document-based approach to Digital Engineering (DE) methods and technologies. Several Systems Engineering Research Center (SERC) research tasks provided insights into facets for a DE Transformation as discussed herein. Research Task WRT-1001 (McDermott et al. 2020) investigated qualitative and quantitative measures that reflect on the value of DE for systems engineering. The WRT-1001 study extracted 350 cited benefits from over 800 published papers on MBSE. The study conducted a survey with over 150 respondents citing diverse benefits of MBSE. These sources enabled the study to derive DESMs that we grouped into four metrics categories: 1) Quality, 2) Velocity/Agility, 3) User Experience, and 4) Knowledge Transfer. The NAVAIR Systems Engineering Transformation (SET) conducted three phases of surrogate pilot experiments focused on applying DE methods and tools in a collaborative DE environment referred to as the Skyzer surrogate pilot. Skyzer demonstrated a new operational paradigm between government and industry based on a SET Framework defined by Naval Air Systems Command's (NAVAIR) leadership. A comprehensive and cumulative summary of the surrogate pilot experiments is in the WRT-1036 Final Technical Report (Blackburn et al. 2021).

This paper discusses the correlated analysis of the DESMs in the context of lessons learned benefits and recommended DE practices from the Skyzer project. The Skyzer experiments "modeled everything" to demonstrate the art-of-the-possible. We use the lessons learned in this analysis, because they rely on DE best practices, methods, models, and tools that should enable efficiencies, and contribute to increased consistency, automation, and productivity. We integrated methods and tools with enabling technologies: Collaborative DE Environment (DEE) supporting an Authoritative Source of Truth (AST) used by both the Government and surrogate contractor teams. The pilot leveraged DEE technology features, such as Project Usage (model imports), DocGen, View Editor, and Digital Signoffs. The evolving DE technologies enabled a new operational paradigm to work directly and continuously in a collaborative DEE to transform, for example, how Contract Data Requirement List (CDRLs) fit into the modeling process using Digital Signoff embedded in models and accessed in a collaborative DEE.

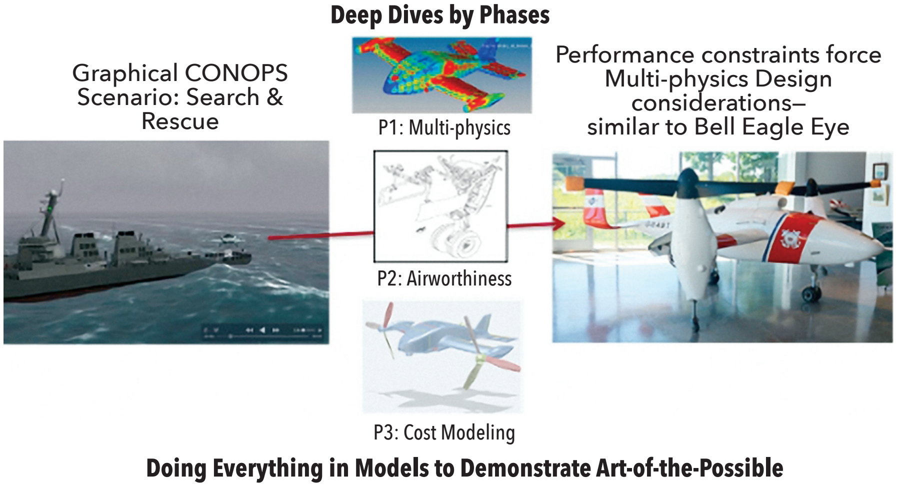

Figure 1. *Graphical CONOPS for Skyzer UAV*

2. BACKGROUND – NAVAIR SURROGATE PILOT FOR SYSTEMS ENGINEERING TRANSFORMATION

In 2013, NAVAIR initiated research of a vision to assess the technical feasibility of a radical transformation through a more holistic DE approach. The expected capability of such an approach would enable mission-based analysis and engineering that reduces the typical time by at least 25 percent from the baseline at that time for large-scale air vehicle systems using a traditional document-centric approach. The research need included the evaluation of emerging system design through computer (digital) models, extended to factor in mission engineering to consider ever evolving threats (Bone et al. 2015).

Eight evolving SERC research tasks spanning seven years informed us, our sponsor and DoD leadership that DE is in use and adoption seems to be accelerating (Blackburn et al. 2017). NAVAIR leadership decided to conduct multi-phase surrogate pilot experiments using different use cases to simulate the execution of the new SET Framework as part of the SET Enterprise Deployment. The overarching timeline from the start of the research until today is in the WRT-1036 Final Technical (Blackburn et al. 2021). Three Skyzer pilot phases evolved and elaborated mission and system analyses and requirements. The Skyzer Concept of Operations (CONOPs) is a UAV that provides humanitarian maritime support for search and rescue use cases as reflected in Figure 1. Key results include unclassified models of examples transformed into workforce development and training.

Phase 1 focused on executing the pilot using a new SET Framework concept. The UAV deep dive included multi-physics analyses such as Computational Fluid Dynamics, structural analysis, weight, and vehicle packaging. Performance constraints such as a cruise speed of 170 knots forced the design away from a helicopter to a design like the Bell Eagle Eye. The government team performed the RFP source selection evaluation in a model using Digital Signoffs. Phase 2 included a ship-based Launch and Recovery (L&R) system to create another capability to research methods for Capability-based Test and Evaluation (CBT&E). Phase 3 developed a landing gear deep dive to examine scenarios for modeling Airworthiness information (for example, process to get a flight clearance). Phase 3 also developed a MBSE Cost Model using the Skyzer airframe characteristics derived from the Phase 1 contractor model. Phase 3 refactored the models to align with the evolving NAVAIR Systems Engineering Method (NAVSEM), and additions identified from modeling of airworthiness and cost.

3. CORRELATING DE BENEFIT CATEGORIES WITH SURROGATE EXPERIMENT LESSONS LEARNED

The 17 Skyzer lesson learned were correlated with the 22 DESM benefits using weights of: blank (0), three (3), five (5), and nine (9), where nine has a strong relationship from underlying aspects of the lesson learned to a benefit. Figure 2 shows the results of 22 DESM categories with the top 6 of 17 lessons learned observed during Skyzer pilot. There is a total weighting score across the benefits categories (row 2) and similarly for each lesson learned (final column computes score for each lesson learned by row). The highest ranking DESMs across the lessons learned were Consistency, Collaboration/Info Sharing, Automation, Information Access, Improve Traceability and Collaboration Environment and AST.

Each subsection below discusses six (6) of the highest-ranking lessons learned. This section also annotates where appropriate the relationship to the DE Strategy Goals [DESG]:

- DESG 1: Formalize the development, integration, and use of models to inform enterprise and program decision-making.
- DESG 2: Provide an enduring, authoritative source of truth.
- DESG 3: Incorporate technological innovation to improve the engineering practice.

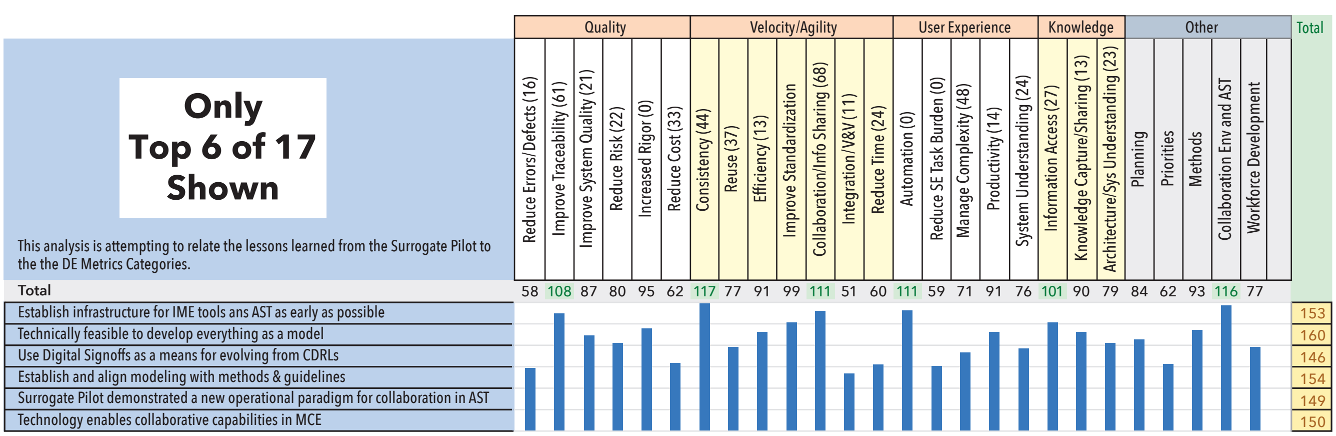

Figure 2. *DE measures correlated to DE lessons learned (Top 6)*

- DESG 4: Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders.
- DESG 5: Transform the culture and workforce to adopt and support digital engineering across the lifecycle.

a. Model Everything in Authoritative Source of Truth

A key decision for Skyzer was to "model everything" to demonstrate the art-of-the-possible. This made everything accessible in descriptive models using the system modeling language (SysML). Descriptive models formalize structure, behaviors, interfaces, and requirement and can replace documents as demonstrated in Phase 1. OpenMBEE enable collaborative access to information for the government and industry surrogate contractor teams (DESG #4). The OpenMBEE DocGen generates stakeholder-relevant views extracted directly from the modeled information enabling SMEs without SysML training, or access to SysML authoring tool to visualize the information in the OpenMBEE View Editor using a web browser. The View Editor allows users to edit or comment on model information directly in a web browser, which can synchronize back into the model.

We used a modeling modularization method (through Project Usages, for example, model imports), which facilitated an implementation of our DEE demonstrating the concept of an AST (DESG #2). We found that modeling everything can eliminate some type of things done in traditional documents. The model modularization method links models together in the AST promoting collaboration/info sharing, information access, to reduce defects, improve consistency, and improve traceability, with all subsumed by the collaborative AST.

b. Model using Methods for Needed Purpose

A goal was to establish and align modeling with appropriate methods and guidelines (NAVSEM). Methods extend beyond processes (what) and identify the artifacts (how) that an organization needs to model to have sufficient and relevant information to make decisions (DESG #1). Descriptive modeling languages should include structure (decomposition and parts), behavior, interfaces, and requirements. A method also defines the types of relationships between the artifacts, which often provides information about cross-domain relationships and dependencies (DESG #1). Technology features that complement methods are the use of View and Viewpoints which are inputs to DocGen. A View and Viewpoint can define the needed model artifacts that are associated with the desired modeling method. Methods, beyond processes define the required types of artifacts leading to consistency, better understanding of the system architecture, standardization, and assessing completeness of a DocGen-generated "specification." Skyzer provided method-compliant unclassified examples transformed into work force development and training (DESG #5).

Different modeling methods support different abstraction levels such as: mission, system, contractor refinement of the system model, subsystem and discipline specific. There are methods for tradespace analysis such as Multidisciplinary Design Analysis and Optimization (MDAO), as well as model management methods demonstrated on Skyzer. The Artifact standardization using specific types of model elements, properties and relationship enables automating validation rules to check for methodology compliance. Authoring clients or using ontologies and semantic technologies enables checks to be done, which permit cross-domain reasoning for decision-making (DESG #1).

Model management methods extend traditional configuration management of documents by tracking and versioning every object within a model, and relates to modeling method validation rules, such as: there should only be one object representing a specific element (traced to the design), because we can use that one object in different model views (diagrams). Project Usage (for example, model imports) help avoid duplicating a representation of an entity in more than one place throughout the models fostering reuse and traceability.

c. Establish Infrastructures for DE Tools and AST Early

The DEE definition and use must occur in a way to establish a collaborative AST (DESG #2) using methods and tool features (Project Usages/Import, DocGen). Phase 1 made slow progress until the establishment of the DEE for information access and collaboration/info sharing. We warn people that tools alone are not enough; one must establish a set of modeling methods that defines the artifacts that the models must produce, and View and Viewpoint/DocGen help by allowing SMEs to define the needed information generated from the models.

d. Technology Enables Collaborative Capabilities in DE

There are evolving technologies that we can incorporate into the overarching DE approach (DESG #3). OpenMBEE extended commercial tools; DocGen is easier to use than other competitors' model-based "generation." NASA created DocGen and View Editor to enable non-modeling SMEs a collaborative way to review models generated from models, and we extended it to create Digital Signoffs to enable decision making directly in a web browser (DESG #1).

Project Usage are a type of model import, supporting reuse, and enabling collaboration and traceability within the AST from mission, system, and contractor descriptive models. Our research has demonstrated semantic technology for tool interoperability between SysML models with discipline-specific simulations (Hagedorn et al 2020) and a Navy Cyber Ontology Pilot demonstration (Blackburn et al 2021).

e. Surrogate Pilot Demonstrated New Operational Paradigm for Collaboration in AST

Phase 1 demonstrated a new operational paradigm for collaborative information sharing in an AST for government and industry to better interact to provide efficiencies during acquisition. This approach was socialized with industry numerous times with positive responses from industry. The pilot demonstrated a SET Framework objective to enable asynchronous insight and oversight by the government in the AST, including asynchronous reviews using Digital Signoffs through information access (DESG #2 & #4).

f. Digital Signoffs for Transforming from Contract Data Requirements List (CDRLs)

Another SET objective was to "transform" away from CDRLs, which we demonstrated using Digital Signoffs that enabled asynchronous reviews through collaborative information sharing. Digital Signoffs link model evidence to criteria required in a CDRL. We determined an approach to use OpenMBEE View and Viewpoints as a means for placing a Digital Signoff directly with model information that provided the needed evidence (Kruse, Blackburn, 2019). Digital Signoffs are model objects that users can update in the View Editor and the signoff information can synchronize back into the model. The template-based digital signoffs can incorporate one or more signoffs, and other information such as risk. We automated digital signoff measures and metrics, as well as demonstrated how to transition a signoff back to TBD, if there was a modification to the associated artifact. Digital Signoffs should reduce cost by transforming/eliminating CDRLs that take on a new form in the model providing greater efficiency, consistency, automation, and standardization. ■

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Acquirer Driven Digital Engineering Transformation

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ABSTRACT

Digital Engineering, like any initiative, should have a clear purpose and direction. For organisations that sit as Acquirers/Clients the Digital Transformation may not seem immediately valuable. However, for this group Digital Engineering can provide opportunities to tightly engage with their supplier network, understand trade-offs through design and upgraded lifecycles and enhanced supplier outcomes.

This paper discusses the benefits and challenges of adopting Digital Engineering in the Concept Phase, where most of the project costs are committed. It highlights that the greatest return on investment for Digital Engineering is during Concept Phase as the flow of authoritative information permeates the remainder of the lifecycle. This presents the case for acquisition agencies to both drive the application of Digital Engineering within their industry and lead by example, through Digital Engineering adoption.

KEYWORDS: digital engineering, model-based systems engineering, acquisition

INTRODUCTION

Digital Engineering, like any initiative, should have a clear purpose and direction. For organisations that sit as Acquirers/ Clients the Digital Transformation may not seem immediately valuable. However, for this group implementing Digital Engineering can provide opportunities to tightly engage with their supplier network, understand trade-offs throughout design and upgrade lifecycles and support enhanced/ immersive reviews.

The broad adoption of Digital Engineering is accelerating as industry sees the commercial advantages; however, this adoption is still relatively slow. Acquisition agencies, such as Government, have influenced this adoption through policy and related strategies (e.g., USA DoD 2018), but have also been slow to adopt the practice themselves. In Australia, agencies such as the Department of Defence and Transport for New South Wales have employed Model-Based Systems Engineering (MBSE) practices on a project-by-project basis, and where stakeholders have identified that a rigorous, data-centric approach can help mitigate risk. This level of adoption across multiple organisations show an initial step towards Digital Engineering but is far from an industry level Digital Transformation.

This paper makes the case that for industry to be more successfully in adopting Digital Engineering, acquisition agencies must both adopt and drive the application of Digital Engineering. It explores the literature and provides an argument for a more comprehensive adoption of Digital Engineering by acquisition agencies.

SCOPE OF DIGITAL ENGINEERING

The United States of America Department of Defence defines Digital Engineering as "an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines" (USA DoD 2018). Digital Engineering spans the system life cycle, this includes the initial concept phase, through design cycles, production, ongoing support, and monitoring, and onto disposal or upcycle of the system. This scope remains the same for a production line systems or one-off designs. For organisations that conduct their engineering across the entire span of the system's life cycle it is possible to exercise control over the implementation of Digital Engineering. For acquisition agencies, whose focus is on the initial concept phase and ongoing support and maintenance (or operation of the system) there poses a significant challenge in implementing Digital Engineering.

Systems Engineering as part of Digital Engineering

The scope of systems engineering (described in the SEBoK (SEBoK 2021) as shown in Figure 1) spans the conception, design, development, production, and operation of physical systems. systems engineering holistically integrates the engineering disciplines being utilised to design a 'System' and interrelates with areas such as Project Management and Product Implementation to realise this system. As such systems engineering forms the backbone of the engineering undertaken in relation to the System, throughout its life cycle. In this context, MBSE (which is a data-centric approach to systems engineering), is a key element of Digital Engineering.

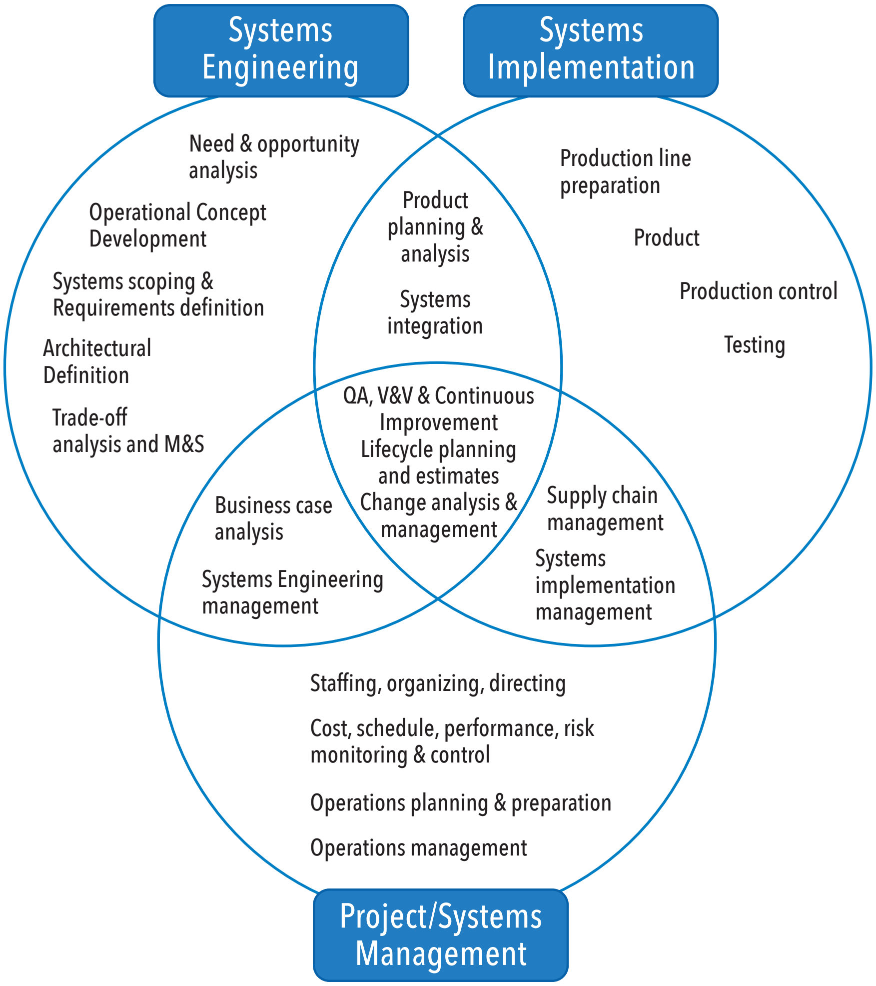

Figure 1. System boundaries of systems engineering, systems implementation, and project/systems management. Redrawn from SEBoK (SEBoK 2021)

In an acquisition agency context, the scope of systems engineering is no different, though part of that scope will lie within supplier agency or agencies. Within the acquisition context, systems engineering provides the comprehensive approach to analyse and combine contributions and balance trade-offs among cost, schedule, and performance while maintaining an acceptable level of risk covering the entire life cycle of a system (paraphrased from DAU 2021).

Systems engineering is making the transformation to MBSE, INCOSE Vision 2025 (Friedenthal et al 2014) states that "Model-Based systems engineering will become the "norm" for systems engineering execution, with specific focus placed on integrated modelling environments". Systems engineers adopt digital technologies that are becoming more readily available, supported by the training and education needed. This brings the discipline of systems engineering in line with other areas of engineering and design such as civil and electronic engineering that employ their model-based tools such as Computer Aided Design (CAD) and circuit board design tools, respectively.

This drive towards digital technologies, and more broadly Digital Engineering, is starting to make a real difference to complex and cross discipline projects that require a "...fully integrated engineering environment..." that provides the Systems Engineer with the "...data integration, search, and reasoning, and communication technologies to support collaboration." (Friedenthal et al 2014). The creation of digital models, both analytical and descriptive, and the integration of these models, provides more efficient and effective support to all the systems engineering activities for the design, development, manufacture, and operation of systems and as a result, mistakes are minimised, design decisions are more effective, and this increases the long-term success of the project.

Benefits of Digital Engineering

Much has been written in the literature on the benefits of Digital Engineering, including those attributed to MBSE. Unfortunately, the published benefits of Digital Engineering are based on non-empirical data, gathered through a 'lessons learned' process following project completion. The decision for employing MBSE in a project is based on the perceived benefits it offers (Henderson & Salado 2020). Once a project is complete, whether deemed a success or failure, one elicits the effectiveness of MBSE \via interview with the people involved in the projects and is therefore subjective nature. Henderson & Salado (Henderson & Salado 2020) do summarise a list of potential benefits, with better communication and information, increased traceability, reduced errors, improved consistency, better accessibility of information and others consistent across the measured, observed, perceived, and referenced categories of benefits.

So, what for the acquirer? Successful projects spend a much higher proportion of their budget on mission definition (Why do we need it? How will we use it?) and requirements engineering than less successful projects (Cook & Wilson 2018). If Digital Engineering, and specifically MBSE is to undergo adoption by the systems engineering profession, then surely the greatest return will be realised in the initial stages of the project lifecycle where MBSE can be implemented to capture systems engineering information in the form of a digital model. Undertaking the Concept Definition, through a Digital Engineering approach, should lead to better communication and information, increased traceability, reduced errors, improved consistency, and better accessibility of information. Whilst this will provide immediate benefits to the acquirer, these benefits should flow downstream to the supplier. Communicating the problem space, the needs, and the requirements of the stakeholders, through a model-based approach, will benefit the supplier before any design of the systems begins.

In 1992 the UK's National Audit Office (NAO, 1992) published their findings of an examination of the Ministry of Defence's past and future initiatives on life-cycle costing. They concluded that "as much as 90% of lifecycle costs may be determined by the decisions made before production of a new weapon system begins..." This obviously places a high importance on improving the quality of the outputs from the Concept Definition phase (Figure 2) and places a high degree of responsibility for a successful project on the acquirer agency. Decisions made by the acquirer commit up to 90% of the lifecycle costs, so reducing the risk of poor decisions by

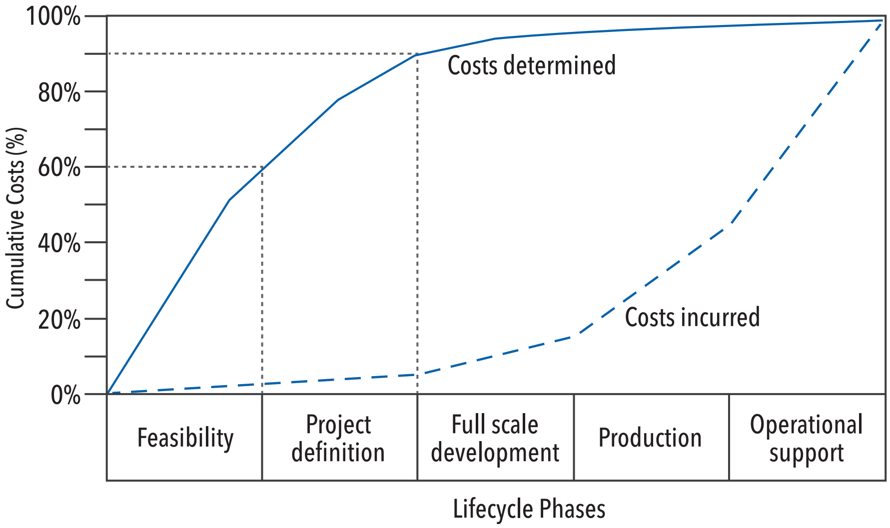

Figure 2. Lifecycle costs - commitment and expenditure. Redrawn from National Audit Office report (NAO 1992)

realising the benefits of Digital Engineering in acquisition agencies, will offer the greatest return of invest in improving systems engineering through a Digital Transformation.

Developing the artefacts from the Concept Phase is an acquirer responsibility. If the acquirer employs an integrated data-centric modelling approach, that provides traceability from strategic guidance to operational scenarios to user needs and system requirements, the acquirer can provide this data to the supplier. This MBSE concept definition will aid the systems designer to better understand the operational and environmental context in which the system is situated and enhance design decision making (supplier responsibility). A Digital Engineering approach allows the supplier to have a clearer and richer understanding of the complex problem, as well as having a more consistent understanding with the acquirer.

Within the INCOSE community there have been several initiatives to improve Digital Engineering, and specifically MBSE, in acquisition agencies. This includes the Model-Based Conceptual Design (MBCD) Working Group, who published an INCOSE INSIGHT Special Edition on Model-Based Conceptual Design (Robinson et al 2014) that argued the case that the aim of MBCD is "not to directly improve the quality of the individual artefacts, such as stakeholder requirements, but to enhance the design of the system concept through improving the means to derive, elicit, analyse, and record the design information as a whole. Ultimately, this aims to increase project successes, with greater overall outcomes achieved for the engineering effort invested." This, and other initiatives, have provided the knowledge base for acquisition agencies to adopt Digital Engineering, however there is a great deal of effort required to improve the maturity of Digital Engineering within acquisition agencies.

THE MATURITY OF DIGITAL ENGINEERING WITHIN ACQUIRER ORGANISATIONS

The Australian Department of Defence used MBCD on various acquisition projects. In 2008 Robinson et al (Robinson et al 2010) applied MBSE to the Ground-Based Air and Missile Defence (GBAMD) acquisition project (LAND 19/7). This project showed that an MBCD approach was "completely compatible with current mandated (document-centric) capability development processes". The approach applied MBCD in employing operational analysis to elicit user needs and derive the system requirements, producing critical acquisition documents such as the Functional and Performance Specification directly, and only from (no word processing text editing), the MBCD Model. This research demonstrated a number of benefits to the acquisition project such as enhanced access to, and communication of information, increased traceability from the project's strategic guidance to systems requirements and improved ability to identify errors and inconsistencies. The Defence Acquisition Project Lead identified that the "...approach produced a valuable project knowledge repository that will ensure continuity during future staff rotations and will allow the [document] suite to seamlessly evolve with the capability definition process" (Robinson et al 2010).

In a 2018 paper Hallett et. al (Hallet et al 2018) found, through surveying Australian Defence personnel, that there was general agreement that while there is a marginal use of information models generated by Defence for acquisition, their development (and increased use) is not directed by the Australian Defence Organisation. Hallett also commented that those information models were only in use for acquisition, and not throughout the evaluation process or later in the system life cycle. Importantly, those interviewed agreed that the state of information model sharing across the contract boundary is non-existent.

More recently, the Systems Engineering Research Center led a collaborative research project the National Defense Industrial Association (NDIA) Systems Engineering Division, and the International Council on Systems Engineering (INCOSE) to benchmark the current state of Digital Engineering (DE) across practicing organisations (McDermott et al 2020). The survey across a broader range of industry, government and academia validated the early finding from Hallett et al (Hallett 2018) finding that most respondents scoring their level of Digital Engineering maturity as low, and specifically that "government lagged industry and academia". Decomposed survey results across survey categories of model usage and management also reflected comparable results. However, with government as the primary acquirer, the survey did note that "...government customers are mandating MBSE on programs, which is driving our digital engineering transformation," suggesting that government understands the benefits that Digital Engineering bring to an acquisition project.

ACQUIRER LED DIGITAL ENGINEERING TRANSFORMATION

For industry in general to be more successful in adopting Digital Engineering as standard practice, acquisition agencies must both adopt and drive the use of Digital Engineering within their industry. In adopting Digital Engineering approaches acquisition agencies provide two key enablers to industry: Firstly, the data-centric artefacts needed for Digital Engineering across the full life cycle of a system. Secondly, the overarching governance and control for the use and acceptance of system data developed and delivered alongside the system as well as the standards and data structures to apply.

Acquisition agencies are responsible for the early definition of the system they wish to acquire, particularly the Mission Definition. As described previously (NAO 1992), concept and system definition activities commit approximately 90% of the cost of a project prior to detailed definition and full-scale production. In

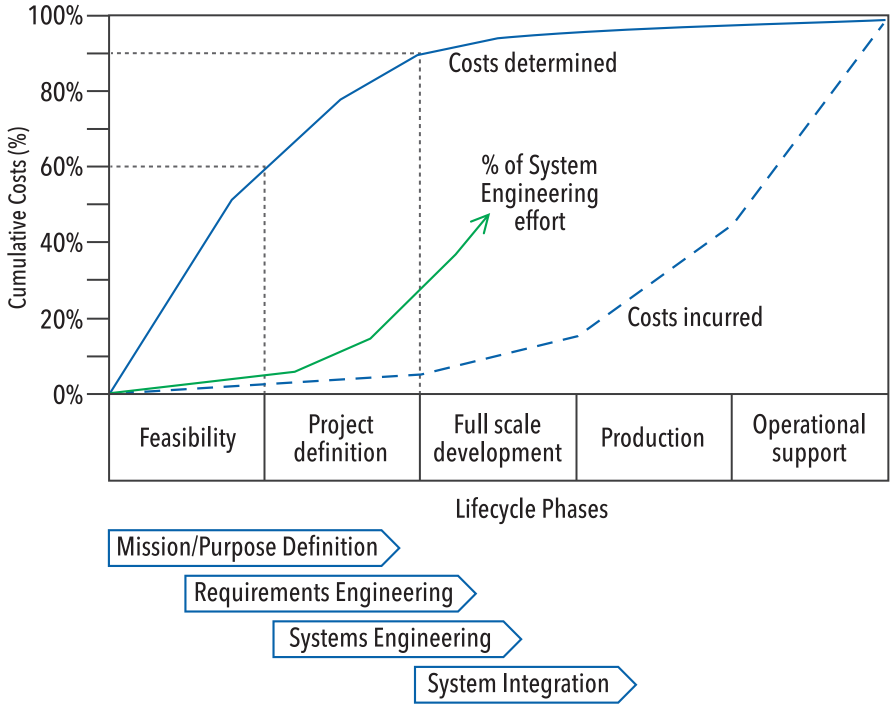

Figure 3. Systems engineering expenditure (Honour 2011) overlaid on lifecycle costs - commitment and expenditure (Redrawn from National Audit Office report (NAO 1992))

discussing the return on investment for systems engineering Honour (Honour 2011) showed that a 15% spend of project budget on systems engineering provides the best result on project outcomes (budget, schedule and quality) and that 40% of that spend should occur during activities such as Mission Definition, Requirements Engineering and Systems Architecting, depicted in Figure 3. During an acquisition project these activities, early in a systems life cycle, need sharing between the acquirer and supplier. In a typical project an acquirer would perform the majority of the Mission Definition, a significant amount of the Requirements Engineering and have some level of input into the System Architecture with the supplier executing the rest. To realise the benefits of Digital Engineering the acquirer agency needs to implement data centric approached to these early life cycle activities. This includes capturing system data in the form of integrated models, simulations, and other structured repositories and, most importantly, sharing those models, simulations, and repositories with supplier agencies. In doing so, supplier agencies will make more informed design decisions, and therefore increase the chance of project success. From experience working with acquisition agencies (e.g., Robinson et al 2010), the authors estimate that once the acquirer establishes a capability in MBSE, there is minimal difference in the initial level of systems engineering effort between document-centric and data-centric approaches. The only difference being that the longer-term systems engineering rework is minimised and the likelihood of projects success increased.

In addition to adopting Digital Engineering approaches within their own organisation, acquisition agencies have a role to play in driving Digital Engineering transformation within supplier organisations (potentially affecting industry wide change). Market surveys have shown that industry are late adopters of new technologies including advances in Digital Engineering technologies such as Building Information Modelling (BIM) (Walasek and Barszcz 2018). This conservative approach leads to gradual shifts across an industry. A key impact that acquisition agencies can have is in providing the leadership and governance of Digital Engineering across the system life cycle and incentivising its application. Hallett et al (Hallett et al 2018) states that supplier organisations see that "There is currently little incentive for suppliers to share models unless contractually obligated", citing a lack of appreciation of cost and management of Intellectual Property (especially with multiple suppliers involved at various stages of a systems development and sustainment) as key issues in acquisition agencies. Mandating Digital Engineering, providing a framework for controlling how data share happens between supplier organisations, defining standards and templates, appropriate data structures and interfaces, and even toolsets to use, is a role that the acquisition agency can take that will promote the adoption of Digital Engineering in supplier organisations.

Benefits to the supplier

When discussing benefits to the supplier it is worth noting that adopting a Digital Engineering approach for system design benefits the supplier organisation regardless of the approach taken by the acquisition agency. Here, benefits to the supplier organisations occurs in the context of acquisition agencies adopting Digital Engineering, providing a level of governance and direction on its use, and sharing their Digital Engineering artefacts, namely models.

Supplier organisations will see potential benefits as early as the tendering phase of a project. Cook et al (Cook et al 2014) explored an approach to model-centric information exchange across the contractual boundary for the purpose of tendering. This paper demonstrated that a tender response that utilised Digital Engineering (in this case specifically MBSE), where all system data passing between acquisition agency and supplier organisation was in the form of compatible models, allowed for the effective evaluation of the tender response. This approach, when coupled with the benefits of increased traceability, reduced errors, and improved consistency (Henderson & Salado 2020) indicates that tender responses will communicate more clearly how the response meets the tender (and importantly how it does not). This clarity should mean better alignment of stakeholder expectations at the commencement of a project and reduce the likelihood (and magnitude) of early project scope change.

Supplier organisations will also see benefits throughout the system life cycle. One of the key root causes for acquisition project failures is a lack of shared understanding between the acquirer and the supplier (Hallett et al 2018). By adopting a Digital Engineering approach that includes the acquisition agencies system data supplier organisations can generate a common understanding. The design and other engineering activities happening are directly traceable to the requirements, mission definition and other key system data. This traceability provides context to the design, opportunities to share information in forms tailored to meet specific stakeholder needs and can provide opportunities for early Verification and Validation (McDermott et al 2020). All of which aim to reduce project risk and improve the relationship between supplier and acquirer.

Challenges for the Acquirer

As discussed above, Digital Engineering is "an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines" (DoD Strategy 2018). This is a valid goal; however, it brings its challenges for the acquirer, and even for an acquisition agency with a mature Digital Engineering capability. The "authoritative sources of system data and models" asks for a single source of system data and models that would be shared across suppliers from different organisations. This raises three key challenges; data protection; data standards and the maturity of the data-centric tools.

Cook et al (Cook et al 2014) identifies that a key challenge for acquisition agencies is information management and controlling the flow of that information between organisations. The acquisition of a capability is a competitive environment, which "mandates careful control of information flow in both directions: the acquisition agency is required to adhere to strict probity requirements and the supplying organisations need to contain proliferation of their differentiating intellectual property that provides them their competitive edge" (Cook et al 2014). More recently, the Aerospace Industries Association white paper provided recommendations that "revise(d) regulations required to provide the government appropriate data rights" and that "intellectual property rights where early phases of mission planning and CONOPs development between industry and government still allow for protection of competing solutions" (AIA 2016). Both papers argue for data protection, whichever direction the data flows, in a digitally enabled authoritative source of system data and models.

Realising the seamless flow of authoritative sources of system data requires standards for that system data and models. As highlighted by Williams, Nallon, and Mendo, (Williams et al 2020) there are many different data interoperability standards from many different standard bodies and consortia that need to evolve and aligning across the industry. Williams, Nallon and Mendo predict that there is a four-year time horizon for that evolution and alignment, but even that seems optimistic to the authors.

Complementing the challenges with data standards is the maturity of the tools. Digital Engineering requires a diversity of tools across the various lifecycle phases and disciplines that can share the data and deliver an authoritative sources of system data and models. For the acquirer, having the right tool, to deliver the Digital Engineering environment is a challenge. There are a significant variety in MBSE tools, with different approaches to the modelling and the environment to deliver it. Despite the age of the Aerospace Industries Association white paper their recommendation to provide "...a government-industry collaborative, secure MBSE framework to support diverse tool sets and controlled data exchange to develop stable, clear, affordable, non-conflicting program requirements" (AIA 2016) is still true today.

SUMMARY

Digital Engineering delivers the opportunity for tremendous benefits, especially when applied early in the life cycle of the engineered system. Adopting Digital Engineering in the Concept Phase enhances that phase and provides benefits to the rest of the life cycle as the flow of authoritative sources of system data from the Concept Phase permeates through the latter phases. The greatest return on investment for Digital Engineering is in the hands of acquisition agencies, as most project costs are committed under the responsibility of the acquirer. Both the acquirer and the supplier have a personal stake ensuring that those committed costs have been robustly determined before any solution design decisions by the supplier.

Acquisition agencies have two roles to play in driving Digital Transformation, leadership, and adoption. Digital transformation influence by the leadership and governance of acquisition agencies must occur, and they must lead by example, through the adoption of Digital Engineering. ■

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Kevin Robinson is the Head of Innovation and Chief Engineer at Shoal Group, with a distinguished career in the field of Guided Weapons in both the UK's Ministry of Defence and Australia's Department of Defence. He has made significant contributions to the development of advanced guided weapons through modelling and analysis, research, and leadership of large cross discipline teams. Throughout his career, Kevin has taken a leadership role in advancing the field of Model-Based systems engineering (MBSE) via his publications and contributions to the systems engineering community. He initiated and chaired Australia's first annual MBSE Symposium, formed and chaired INCOSE's Model-Based Conceptual Design Working Group, delivered a keynote address to INCOSE's international symposium in 2016, and has made contributions to INCOSE's Systems Engineering Handbook and related standards.

Tommie Liddy is a Senior Systems Engineer who specialises in Model-Based Systems Engineering (MBSE) techniques on a wide range of large and complex capability design projects. He is currently employed by Shoal Engineering as the systems engineering Practice Lead and is also a member of the Engineering Leadership Team. Tommie has been the technical and project lead for defence and transport capability design projects, run teams of engineering specialists conducting detailed technical studies and worked on Systems of Systems (SoS) problems to understanding program-level capability. He holds bachelor's degrees in Mechatronic Engineering as well as Mathematical and Computer Science, is an INCOSE CSEP and an Adjunct Lecturer at The University of Adelaide.

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