Enterprise System-of-Systems Model, Digital-Engineering Transformation Summary Report of SERC Technical Report SERC-2018-TR-109

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Executive Summary

In June 2018, the Office of the Secretary of Defense for Systems Engineering (DASD/SE) released the Department of Defense (DoD) Digital Engineering Strategy, a comprehensive strategy for the transformation of DoD engineering methods, processes, and tools to the digital age. The strategy outlines five strategic goals for the transformation, targeted to "promote the use of digital representations of systems and components and the use of digital artifacts as a technical means of communication across a diverse set of stakeholders, address a range of disciplines involved in the acquisition and procurement of national defense systems, and encourage innovation in the way we build, test, field, and sustain our national defense systems and how we train and shape the workforce to use these practices." [1] These goals center on the definition, development, and use of a program "authoritative source of truth" – a government/contractor shared set of digital data and models that move away from static and disconnected program artifacts toward a fully integrated digital information exchange in order to improve the accuracy and timeliness of program decisions across the system lifecycle.

This report presents the results of a research project that was conducted in parallel with and independent of the development of that strategy to understand how that strategy might evolve and change the way the DoD conducts acquisition of new systems and supports existing systems. A multi-disciplinary research team conducted a qualitative analysis of that transformation, using interviews of over 25 stakeholders currently involved in Digital Engineering (DE) initiatives across multiple DoD agencies, NASA, and the FFRDC/UARC community. These interviews were then used to develop conceptual models describing what that future DoD acquisition enterprise might look like, given success of DoD DE initiatives. These conceptual models were developed independently from the released strategy, but the interview process found strong alignment with the strategy across the stakeholder base, so the models in this report were organized to align with the five goals of the DE strategy.

The research was targeted specifically on the impact of DE transformation to the DoD acquisition enterprise – the government program offices, acquisition professionals, and contractor practices that develop, operate, support, and maintain defense systems. It provides the first holistic assessment of how that transformation might evolve, and what benefits can be expected from the change. The research was conducted around a set of "central questions of interest" provided in initial interviews with DASD/SE sponsors. These are:

1. How will DE help the acquisition enterprise respond to the realm of the possible with warfighter needs?
2. What are the opportunities that can be gained from deeper information in the authoritative source of truth?
3. How will DE make the acquisition process more efficient and reduce rework?
4. Can DE make it easier to ingest new processes and incorporate acquisition expertise into acquisition tools?
5. How do DE documented architecture principles add value to development and acquisition processes?
6. How will DE environments capture and maintain lessons learned within and across programs?
7. How can DE improve the performance of the acquisition workforce, at every skill level?

These questions address the perceived value of the DE transition to DoD acquisition. The research methods used in this project are designed to bring focus to the value of enterprise level transformation outcomes and what are the leading indicators of change that would reflect achievement of those outcomes. The methods center on three questions: what are the desired change outcomes, who will lead/oppose the change and how will they interact to affect it, and what are the enablers and barriers to the change process? A set of qualitative tools were used to assess these questions – tools adapted from a large base of research on enterprise and innovation-driven transformation processes.

The project produced five conceptual models reflecting the future DE-enabled acquisition enterprise, one for each of the goals in the DE Strategy. The systemigram conceptual modeling tool, which includes both a narrative of change and accompanying concept diagram, was used to capture the combined views of the interviewed stakeholders. The five models are 1) the Authoritative Source of Truth, 2) Digital Engineering to inform enterprise and program decision making, 3) the Digital Engineering infrastructure, 4) technical innovations to improve engineering practice, and 5) changing workforce and culture. These models were reviewed in a workshop setting with the sponsor team and approved for publication is this report.

The model results had immediate use in informing the sponsor of potential metrics reflecting the performance or DE change initiatives. The systemigram diagram naturally produces insight on change metrics, which are the outcome of the relationships modeled in the diagram. In addition, the diagrams are useful in agreement on a lexicon that describes the future system, identification of all involved stakeholder groups in the process and their individual value sets, and identification of key enablers and barriers to enterprise change. These results are documented in the report.

Taken as a whole, this process provided significant insight on three central themes: what is the Authoritative Source of Truth how will it be provided, governed and used; how will DE transform the work that defense acquisition program offices perform, and how should they prepare; and how should the DoD enact change to their workforce and culture to ensure a successful transformation? The report identifies a set of recommendations for future research that addresses each of these themes.

This is a summary report taken from the full task order final report SERC-2018-TR-109 which is available on the SERC website at https://sercuarc.org/publication/?id=197&pub-type=Technical-Report&publication=SERC-2018-TR-109-Enterprise+System-of-Systems+Model+for+Digital-Thread+Enabled+Acquisition.

1 Introduction and Background

The Department of Defense is embarking on a set of initiatives to transform DoD acquisition processes and guidance for engineering and manufacturing development in a full digitally enabled environment. The DoD Digital Engineering Strategy released in June 2018 outlines five strategic goals that reflect policy and guidance, support for pilot programs, support for implementation plans, and tools/standards [1]. The strategic goals are to:

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 technical innovation to improve the engineering practice.
4. Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders.
5. Transform the culture and workforce to adopt and support digital engineering across the lifecycle.

The SERC is supporting Digital Engineering (DE) efforts through research tasks such as Transforming Systems Engineering through Model Based Systems Engineering and the Engineered Resilient Systems program. These efforts are focused on assessment and development of collaborative digital engineering environments as an evolution in processes, methods, and tools. However, additional research is needed to characterize the related path for the DoD acquisition enterprises.

Previous research in the SERC defined a set of methods and processes to model transformative change in large scale enterprises—the enterprise systems of systems (ESoS) methodology. In this research task, this approach will be used to develop enterprise transformation model that can be used to provide insight into the value of different acquisition strategies and incentives. "Owning the technical baseline" means that "[DoD] program managers and personnel have sufficient technical knowledge of their engineering development programs to ensure program success by making informed, timely, and independent decisions to manage cost, schedule, and performance risk while ensuring disciplined program execution." [2] Owning the technical baseline will allow DoD to respond more quickly and without disruption to changing mission needs and to opportunities for technical innovation. Central to this is the DE strategy to establish an enduring, authoritative source of truth.

This project was conducted to better understand how DE will support owning the technical baseline and how it will affect the corresponding acquisitions processes. The Digital Thread, Digital Twin, and Model-Based Systems Engineering (MBSE) are key enablers that will allow Program Managers (PMs) to reduce both technical and programmatic risk through better interface management, deeper collaboration, understanding the impact of design choices on cost and schedule, etc. It is expected that this impact could reach much further, not only changing the way information is shared in the acquisitions context but fundamentally changing the business eco-system: competition, risk attitudes, business models, etc.

The transformation from a primarily paper-based set of decision tools to a digital enterprise will likely make a number of current business processes obsolete, change current relationships between the defense acquisition community and the defense industry, adjust roles and associated jobs, and shift stakeholder perspectives on value in the enterprise. One should expect that the various policy makers, user communities, acquisition communities, and contractor communities will both embrace and oppose transformative changes in ways that maximize their individual values. How these complex interactions among stakeholders will affect the acquisitions eco-system is difficult to predict.

This research was conducted to evaluate the impacts of DE on current DoD acquisition enterprise processes. The following questions guided the outcomes of this research:

- What changes are likely to emerge from the transition to DE processes, methods, and tools?
- What are the enablers and barriers to such innovation in the DoD acquisition enterprise?
- What stakeholders will be affected and how will they likely embrace or oppose change?
- How might stakeholders be incentivized to embrace innovation and how will this be measured?
- What are the leading and long-term indicators of change?
- How might the value of such changes be predicted and measured?

Within this acquisitions enterprise, major areas of competing goals will include shared government and contractor access to the set of design data, scientific and technical analyses, decision trades, process and tool data, development approaches, and even engineering notes and discussions that form the project technical baseline. Shared goals will not be developed with mandates, but will be enabled through innovations in methods, processes and tools that create “win-win” strategies between stakeholders. Changes that focus on the enablers and barriers to effective innovation in these processes are needed, and these are the primary drivers of an enterprise view.

While MBSE is well-developed and broadly adopted in the defense industry and beyond, the full scope of a DE transition is still in the early stages of development and adoption. Besides the DoD efforts on digital engineering, several similar efforts are underway in industry: digital threads (Air Force), digital twins (by GE or Siemens), digital tapestry (Lockheed Martin), model-centric engineering (JPL/NASA), etc. Although digital or model-based approaches towards systems engineering and acquisitions are clearly the path to the future, there are still significant hurdles to overcome. In addition, most of the advances so far have focused on better support for traditional SE methods in a traditional acquisitions context. In this research task, the aim was to lay the foundation for a digital thread enabled acquisitions ecosystem in which the processes (and potentially even organizational structures) are updated to best take advantage of the new digital engineering capabilities. The questions of how the acquisitions ecosystem will be affected by digital engineering and how best to facilitate the corresponding transformation are the focus of this report.

In particular DE will integrate systems engineering, product design, development processes, program management, and related documentation—providing much greater access to and insight into the program technical baseline. How the government and industry participate together in the process, and share appropriate baseline data, is an area that will create both significant value and risk. Identifying the components of the process and baseline that create shared value is critical, and enabling innovations that enable trusted collaboration will build a pathway for success. An enterprise model is needed that identifies appropriate integration of the people, resources, processes, institutional outcomes, and policy changes that in the long-term will transform the acquisition enterprise. This research task has been the first step toward developing that model.

The task used a qualitative research method based on structured interviews to derive a holistic model of the defense acquisition enterprise transition to DE. The generated interview data was encoded and diagrammed in a conceptual model using the systemigram formalism [3]. The conceptual model was generated via a series of narratives generated in the interview process, and refined in design workshops with key stakeholders in the enterprise. This method follows a formal process for documenting enterprise transformation as a multi-level model previously developed and demonstrated in SERC ESoS research [4] [5].

An interview protocol was developed to encourage a diverse set of DE stakeholders to speak openly about the process of DE enterprise change. The project interviewed 25 stakeholders across 15 project visits, and the resulting interview responses were used to create a consolidated narrative describing the transition process. The anecdotes provided by these stakeholders were then diagrammed using the systemigram process that creates a combined narrative and diagram of key aspects of the “story.” In the interview process, the research team found strong consistency between the interview narratives and the DoD DE Strategy, even though that document was published at the end of the process. Based on consistency of these views, the systemigrams were organized into 5 narrative/diagram sets – one for each goal in the DE Strategy document. The systemigrams were reviewed in a workshop with the DE Strategy authors and updated from that workshop to form the basis of this report. Section 2 of the report describes the methodology used, and Section 3 provides the systemigrams.

Because an enterprise transformation is an innovation process that unfolds over time and with many incremental advances, and additional workshop was conducted with the sponsor team to help understand the associated innovation landscape that will drive the DE transformation. The workshop used the “Three Horizons” facilitation tool to map that innovation landscape [6]. These results are presented in Section 4.

The process of developing the conceptual models of transformation leads to a set of initial artifacts that can be used to computationally model the transformation process. These are identification of key stakeholder groups and their values, identification of potential metrics that would reflect the process of transformative change, and identification of enablers and barriers to change that must be incentivized or overcome to succeed. These are discussed in Section 5. In addition, the systemigrams provide an initial broad lexicon that can aid in agreement on key terminology and model ontology for future use. Section 5 includes and initial presentation on this topic.

This report documents the initial stage of an enterprise transition model – the conceptual definition. Section 6 provides a discussion of next steps and future research that would be needed to build a set of computational models of enterprise change.

2 Methodology

This section discusses the research methodologies used in the research task reported here.

2.1 Methodology Background

This task employed a research methodology informed by communities of practice in enterprise transformation, system-of-systems, innovation systems, and social innovation fields. The primary resources for the modeling process documented herein derive from previous SERC research on Multi-Level Socio-Technical Modeling and Enterprise Systems or Systems Analysis [4] [5]. The SERC ESoS line of research is to develop and evaluate a methodology for modeling and analyzing enterprise systems. This work defines an enterprise system as a set of interacting organizations that serve a purpose yet have no locus of control (the DoD acquisition enterprise meets tis goal).

The qualitative facilitation methods used were further developed in the Assessing Innovation Impact Potential Toolset developed by the Global Knowledge Initiative and Georgia Tech Research Institute under sponsorship of the Rockefeller Foundation [6]. These methods were developed as a forward-looking process to provide decision makers with greater insight and confidence into the process of assessing the potential of innovation to impact a problem or change strategy. The result was a customizable toolset to assess the future impact that innovation can deliver in a system to tackle particularly complex problems.

Well-structured narratives in the system architecting process are critical to the understanding of emergence [9], which is core to the ESoS evaluation. Purposeful development of such narratives provides the architectural context needed to engage the stakeholders in a discussion of the SoS characteristics. The narrative serves as a mental expression of different events, phenomena, or observations as episodes that have meaning in the mental domain of the stakeholders [10]. Thus, the process of determining ESoS perspectives begins with a narrative. This process is at the center of the research documented in this report and the tools used provide an example of the insight that can be gained by analyzing a complex enterprise like the DoD acquisition enterprise in this way.

David Snowden, in his research on narrative knowing in complex enterprises, discusses the use of narrative fragments or “anecdotes,” in contrast with full stories, as enabling the researcher to create a blend of stakeholder anecdotes with their understanding of the situation to create a contextually meaningful course of action or strategy [11]. The anecdotes that people relate to the larger story, when queried, become like components of the system in a human centered design process, allowing relevant explanatory models to be built that conceptualize the whole of the system. To explain potential emergence in an Enterprise SoS, the research team collects anecdotes that discuss the present enterprise and possible emergent changes in the future, which are collected with interviews or other facilitation tools. These are collected into a formal framework for modeling the enterprise discussed in the next section.

2.2 Enterprise SoS Analysis Method

The core of the enterprise SoS analysis process is a multi-step data collection and characterization methodology for modeling complex systems [4] [5]. The initial steps are intended to carry background research into an expert forum where the critical aspects of the research are evaluated via interviews or in a workshop setting. The purpose of this effort is not to arrive at a set of answers, but to arrive at an understanding of how the enterprise is organized and might change in response to emerging systemic changes.

The comments and information gathered from stakeholder narratives are fed into the first steps of the methodology to lay the foundation for the study and modeling efforts. All steps will not be completed for this effort as the project will not be creating a computational model.

Figure 1 provides a graphical depiction of this process as tailored for this project. Figure 2 describes the primary analysis tools. The analysis starts with an organizational framework that represents a complex enterprise as a multi-layer enterprise architecture. The process uses a brainstorming tool called a context analysis matrix to aid in understanding of the enterprise at multiple layers and identifying primary abstractions for a model at each layer.

1. **Context Analysis**
2. **Central Questions of Interest**
3. **Identify System Structure & Phenomena**
   - Background Research
   - Interviews
4. **Visualize Relationships**
   - Systemigram Narratives & Diagrams
5. **Identify Areas of Exploration**
   - Innovation System Analysis
   - Key stakeholders
   - Critical enablers & barriers to change
6. **Identify Data Sets to Parameterize**
   - What are the measurement areas that will drive change?
   - What measures are collected versus what should be collected

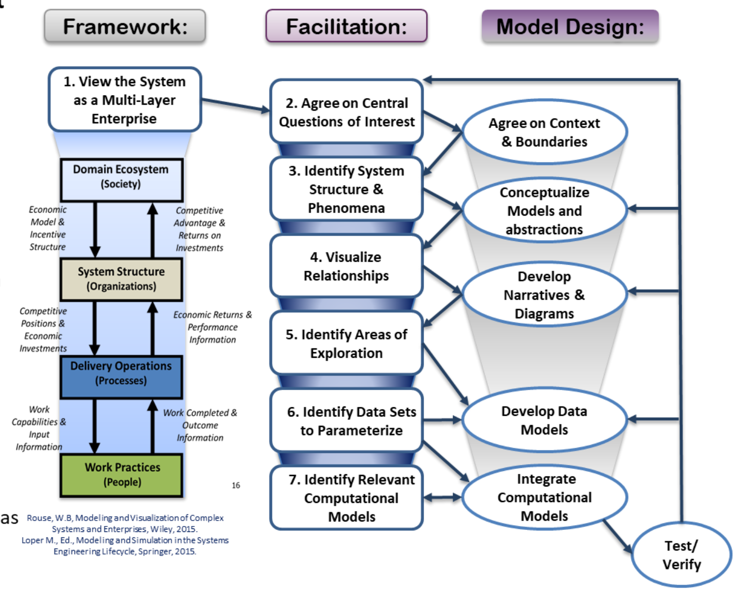

Figure 1. Full Enterprise Analysis Process and Process Steps.

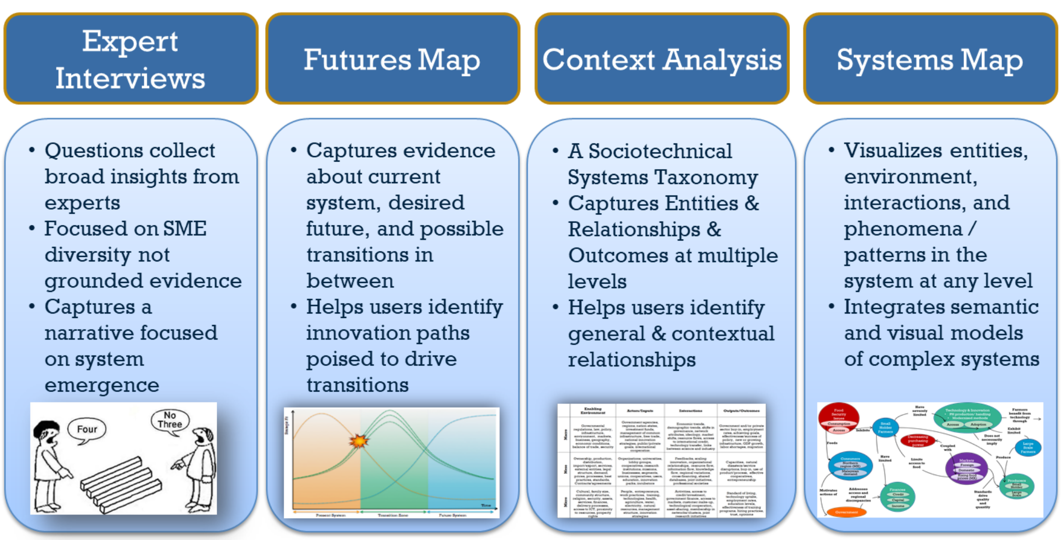

Figure 2. Primary facilitation tools

From that artifact, a discussion with the primary sponsor of the project produces a set of “central questions of interest.” These are the questions the resulting model should answer. This step serves to set boundaries for the model to a context and strategy focus where specific outcomes can be identified. From here the process attempts to map the enterprise using a series of stakeholder interviews, expert workshops, and background research.

The project used a unique interview protocol developed from theory of innovation driven transformation to elicit narratives from key stakeholders who are familiar with DE initiatives in the U.S. government. The interview protocol is structured around discussions of possible emergent futures. It is a purely qualitative in nature, and is designed to collect a breadth of perspectives from as diverse a stakeholder set as possible.

Once the data collection is complete, an enterprise system map is created from the various perspectives and anecdotes collected in the interviews, context analysis, futures map, and additional desk research. The system maps are developed using the narratives collected and a systemigram diagram. The interview narratives from the core of the systemigram process. In this project, over 70 pages of collected interview transcripts were consolidated into a single 11-page enterprise narrative organized thematically. This narrative development process is the first part of “art” of the methodology, best performed by researchers experienced in the process.

Once the completed consolidated narrative is finished, the research team gathers to create the systemigrams. While the systemigram narrative and diagrams naturally span multiple layers of the multi-layer enterprise model, it is important to focus at least one systemigram on each of the four layers of the enterprise in order to gain a complete insight into the enterprise change. Systemigram diagrams are created by literally mapping text phrases in the consolidated narrative into the diagram in a noun-verb-noun phrase format. The diagrams are constructed using the systemigram formalism, focusing on extracting the appropriate components of the larger narrative in relation to the systemigram “story” and building a diagram that can be used to engage a stakeholder discussion of the story. Initial validation of the systemigrams is then completed in workshop facilitations with key stakeholders that discusses and updates the “story” in the diagrams. The systemigrams form the central conceptual modeling artifacts of the research for further use. However, they do represent the exact words of the stakeholders in the interview process and modeling success is dependent on effective elicitation of stakeholder perspectives.

At this point the systemigram diagrams and other artifacts can be used to begin structuring more formal models. The end goal is to provide a set of conceptual modeling artifacts that inform computation models of enterprise organizational change strategies. These are left to later research in future project phases.

An immediate outcome of the process is the generation of a lexicon or terminology for the system. This is a natural outcome of the narrative process, as the narrative consolidations will integrate multiple stakeholder descriptive terms around model components. It is recommended that terminology is agreed upon by the stakeholder community before computational models are constructed.

The systemigram diagrams are then used, by studying the relationships in the diagrams, to identify a set of metrics that will serve as leading and long-term indicators of enterprise change. This is associated with Steps 5 and 6 of the Enterprise Analysis process of Figure 1. These measures serve as the primary input and output measures of a computational model set. An initial list of metrics is provided in Section 4, but these have not been through stakeholder review and will be further refined in follow-on research.

3 Interview Narratives and Systemigram Models

This section provides the consolidated narrative and diagram for each of the five DE strategy initiatives, and a sixth narrative and diagram related to digital information exchange.

1) The Authoritative Source of Truth
2) Inform Enterprise and Program Decision Making
3) Digital Engineering Infrastructure
4) Technical Innovations to Improve Engineering Practice
5) Changing Workforce and Culture
6) A Lexicon for Exchange of Digital Engineering Data and Models

How to Read a Systemigram: When a problem or issue is sufficiently complex or unstructured there is a period of information collection that is a first step to defining potential engineered solutions. A set of heuristics guides that collection. The results of that collection may be unstructured itself but basic tools like mind maps can be immediately used to start structuring the space. This process builds a "model framework" for the system. The model framework is a conceptual view of the system model that captures key characteristics like boundaries, organizations, stakeholders, policies, information flows, etc. It is in effect capturing the architecture of the system with respect to the problems or issues at hand.

Checkland's Soft Systems Methodology recommends that we express problems, issues, or opportunities in the situation system where they are encountered before proceeding to a conceptual modeling phase. At this point verbal narratives or picture diagrams are most effective at expressing the situational aspects. This narrative describes a problem, but to introduce solutions to the problem you need to understand the variables that form the root cause of the situation. At this point more formal modeling becomes useful, but it is difficult to communicate the architecture of the system with a computational model. An interim step that provides a visual model of the system and the context of the issue at hand was introduced by Checkland using concept of rich pictures.

Blair, Boardman, and Sauser developed a formal visualization approach call the "Systemigram" that captures the conceptual model in a systems context and provides a good way to transition between narrative and computational modeling [3]. The systemigram combines a narrative discussion of the system and transformation strategy with a 1-page diagram that models the narrative as a set of nodes and links. When used properly the systemigram provides the architecture of the system that can be used to guide creation or use of more computational models. It is developed from the narrative text, which may be a compelling descriptive view of the system and its dynamics, or a strategic text written to analyze the behaviors of the system and directly produce the diagram. A formal use of the systemigram tool is guided by the following basic rules:

1. The diagram fits on a single page.
2. There is a beginning and an end; the main flow of the story is upper left to lower right.
3. Entities are nodes, links, inputs, and outputs. Nodes are key concepts, phrases, or nouns representing entities or conditions.
4. Links represent relationships and flow between nodes; they include verb phrases identifying transformation, belonging, and being. Links should not cross each other.
5. Nodes may contain other nodes identifying other diagrams or groups. This supports understanding of multi-layer abstractions and aggregation points.
6. The layout of the diagram should be arranged to bring attention to the different levels of perspective it the system. Think "why," "what," and "how."
7. Color is used to highlight particular concepts and transformations. In the diagrams to follow the colors are used to represent the four different enterprise layers.

3.1 SYSTEMIGRAM 1: THE AUTHORITATIVE SOURCE OF TRUTH

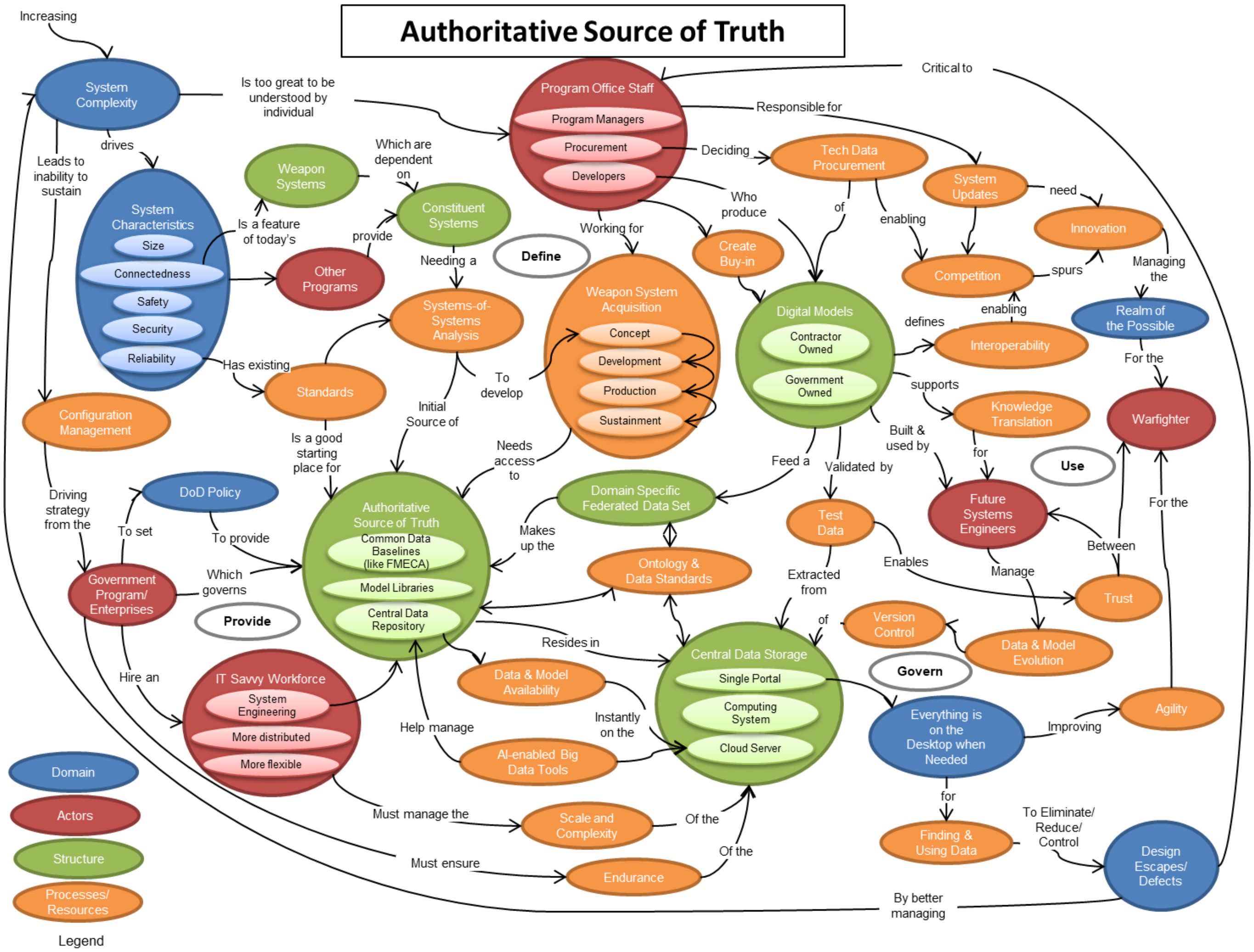

Figure 3. Systemigram 1: The Authoritative Source of Truth.

Questions linger over what is considered to be the Authoritative Source of Truth (AST) and why the government should pursue DE and the AST. As to why, increasing system complexity is driving today's system characteristics like size, connectedness, safety, security, and reliability. Today, a major acquisition development program is dependent on other programs and systems, and these characteristics have become dominant features in weapon systems. New weapon systems are dependent on multiple constituent systems, and effective documentation of architecture and robust system of systems analysis has become a necessary step in the development of new system concepts. Management of complexity across the conceptual, development, production, and sustainment must have access to a large set of historical and current operations data. As to what, this is the authoritative source of truth - the central data repository for all program information. The system of systems analysis, completed in the concept phase of a new system, provides the initial source of truth data. However, this is a significant change in the way systems are developed today. It will be a learning process to evolve exactly what the AST contains. Reliability related design, test, and performance data is a good place to start because there are existing data standards in this community to build from. Common data baselines like Failure Modes, Effects, and Criticality Analysis (FMECA) are created in the community today. As model based systems engineering becomes more prevalent, the AST will become the central repository for all program data and various model libraries, and additional standards like FMECA will be created to organize and aggregate the data across the program lifecycle.

With increasing complexity, the systems engineering community is in general agreement that they can no longer effectively sustain configuration management in SoS. Following other industries like logistics and finance, there is need for data-driven configuration management strategies. This is pushing government and program office enterprises to set DoD policy for DE transformation and a move from paper program baselines to the data-driven AST. Government program offices will most likely govern the AST for a program, but it will consist of a number of domain specific federated data sets that come from various government entities and contractors.

In addition, the community has come to understand that the level of system complexity today is too great for any individual program office staff to maintain wide enough system knowledge to effectively make decisions related to program management, procurement, and development of these systems. Program offices must produce the digital models and data or obtain these from contractors. Government engineering teams will produce digital models that will be exchanged with contractors, who in turn will exchange their models with the government sponsors. This should gradually replace paper specifications and architecture frameworks to feed the domain specific federated data sets. Procurement staff in the program offices will work with engineering to make decisions on tech data procurement early in the development programs. Leadership in program offices must create buy-in between government and contractors for the shift to digital models and away from paper.

The AST will reside in a central data storage repository, most likely a cloud server. In order to achieve this cloud model, a significant effort in ontology development and data standards is needed. The AST will be data and models that are instantly available to program personnel in the cloud server. The government/program enterprises must plan for and ensure the endurance of the central data storage across the system lifecycle. In this process, there will be a need to hire and gradually shift toward a more data and IT savvy workforce, who must manage the scale and complexity of the central data storage. Commercial advances in artificial intelligence, big data, and machine learning should enable tool development to help manage the AST and data store.

Digital model and data validation will be a concern. This should lead to a rethinking of how development and operational testing is done in the DoD. Design Models and data validated by test data will become part of the data entered and extracted from the central data store. Shared access to validated models and test data will enable increased trust between the systems engineering community and the operators in the warfighter community, leading to acceptance of new practices.

The benefit to central data storage is a single portal to all program information. The outcome will be everything is on the program office desktops when needed. This will make it much easier to find and use data, and a consensus among early adopters of DE is that this will significantly reduce or eliminate design escapes, or defects that persist to later lifecycle stages. Over time this benefit will be critical to program office staff in their struggle to better manage system complexity. The ease of access to program data should also improve agility, with direct benefit for the warfighter.

A critical aspect of the AST is the increasing use of model-based engineering. Digital models will be built and used by future system engineers, who will take on the primary role of data and model evolution as well as version control of the central data store. Although this is not new in systems engineering, it will become the primary role. Digital models also support knowledge translation between disciplines and enterprises for systems engineers.

As programs move toward operations and sustainment, program offices become responsible for system updates. Digital models will define and control interoperability across future systems. This, along with good decisions in the procurement of digital technical data, will enable competition in future system updates, spurring much needed innovation. Good system architectures with good system model and data baselines will become essential to managing the realm of the possible for the warfighter and their systems.

3.2 SYSTEMIGRAM 2: DIGITAL ENGINEERING TO INFORM ENTERPRISE AND PROGRAM DECISION MAKING

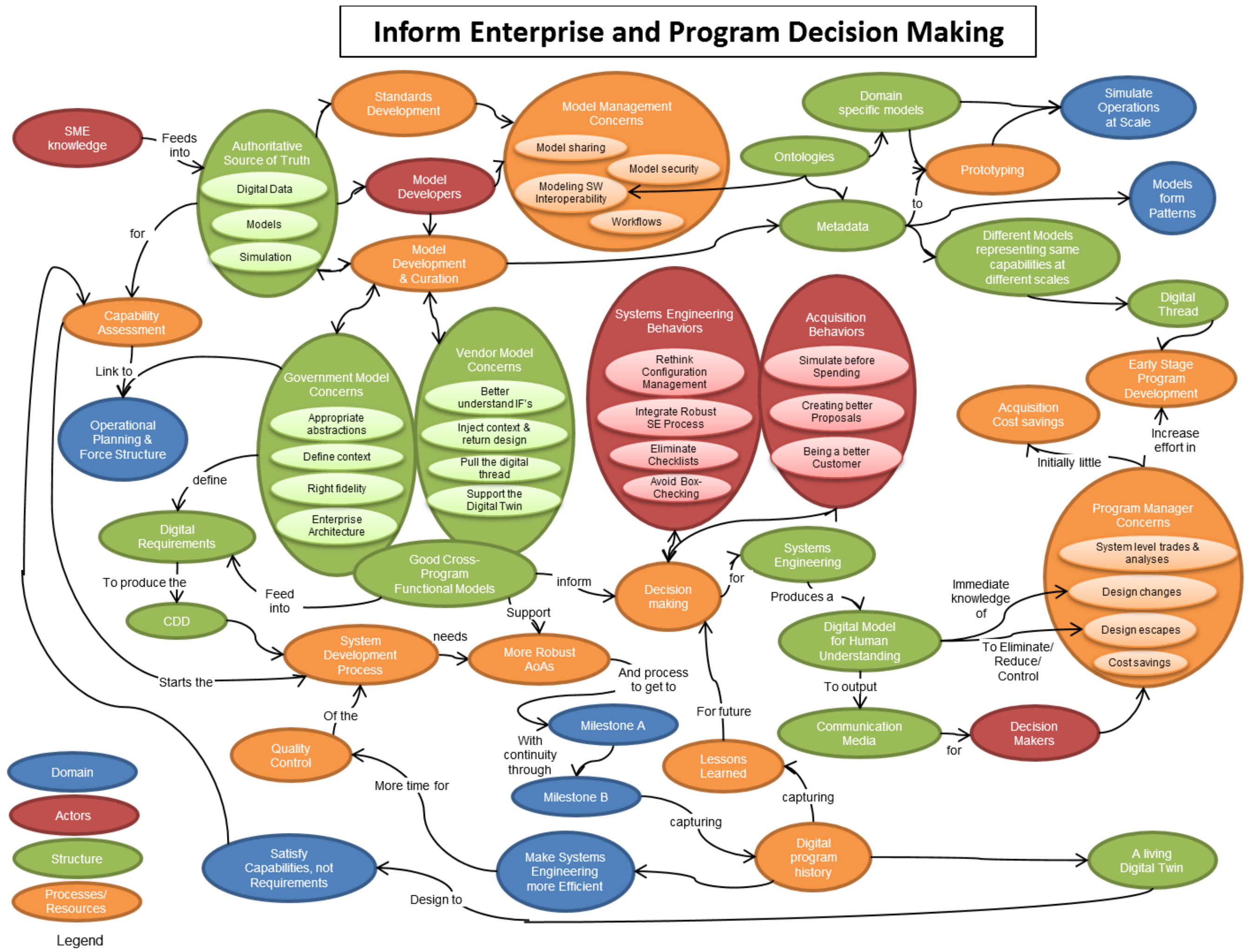

Figure 4. Systemigram 2: Inform Enterprise and Program Decision Making

Given the widespread transformation to Digital Engineering, there are questions over how will it be used to inform enterprise and program decision making. The Authoritative Source of Truth (AST) will be a core component as program data, information, and knowledge shifts from inaccessible documents and stove-piped program offices to collaborative access in the AST.

Subject Matter Expert (SME) knowledge will be fed into the AST in the form of digital data, models, and simulations to be used for capability assessments linked to operational planning and force structure. Model developers will need to focus on model development and curation across a large set of government and contractor models. Previously these may have been standalone and “stove-piped” between model development teams. Model developers will need to address new model management concerns such as model interoperability and model sharing, modeling software tool interoperability, new modeling workflows, and model access and security concerns. Government and contractor teams will need to cooperate on model development and curation. Government will be primarily concerned with enterprise architecture definition, leading to digital representation of CONOPS and requirements. Government models will help define the context for the systems of systems more explicitly, and a learning process through pathfinders will help settle on appropriate levels of abstraction and the right level of fidelity for government developed models. Contractors will inject their models into the government context and jointly establish better upfront understanding of interfaces. The contractor will have primary responsibility for "pulling the digital thread" across the development effort, and capturing a "living digital twin" from the design to support the full program lifecycle. This should result in good cross-program functional models to support more robust analysis of alternatives (AoAs), feed into digital requirements baselines, and inform decision making. Future digital requirements will generate program Capability Definition Documents (CDDs) and other upfront program documentation.

The AST should also be used for government capability assessment processes that will link the government models to defense operational planning and force structure assessment. The link between the AST and the capability assessment process should carry forward into digital CDDs to start the system development process. This link and good program functional models will support a recognized need for more robust AoAs and process that carry the AST through Milestone A with continuity to Milestone B. The continuous capture of digital program history is essential for creation of the living Digital Twin. The DE community consensus is that this will make systems engineering more efficient, giving systems engineers more time for quality control of the system development process.

Good cross program functional models will inform decision making for systems engineering teams. Data and model artifacts extracted from the AST will produce a unique set of digital model artifacts targeted at improved human understanding of the program technical data. This will be output to communication media for decision makers who are addressing typical program management concerns such as system level trades and analyses, requirements and design changes, and management of design escapes and defects. A key benefit of this "digital model for human understanding" will be immediate awareness of design changes and an opportunity to eliminate, reduce, or control design escapes. The long term outcome should be program lifecycle cost savings and shortened program schedules. Of note in this process is that program managers should expect little acquisition cost savings as these will be realized later in the lifecycle. While an increase in effort in early stage program programs development with upfront investment will be needed, this should accelerate the overall development schedule.

This approach to knowledge sharing and decision making should gradually change the behaviors of systems engineers and acquisition professionals. DE is all about good systems engineering and should lead programs to integrate a more robust SE process. The "box-checking" mentality that pervades much of SE practice should be avoided and checklists eliminated in favor of the digital model for human understanding. In the long term, programs will rethink configuration management practices which today produce static and unsustainable artifacts. In the acquisition community, there should be an increase in simulation based acquisition, or "simulate before spending," leading to the creation of better proposals and allowing the program office acquisition professionals to "be a better customer."

The process of model development and creation and model interoperability will produce new outcomes across programs. Model curation will produce metamodels and metadata that design and decision making across the engineering disciplines. Metamodels will be enabled by the development of standard ontologies that support model sharing and by standard abstractions, leading to more efficient domain specific model development (and languages) that ease reuse across programs. One outcome will be improved models and data supporting simulation of operations at larger scales. Shared metadata and domain specific models will also be used to inform more and better prototypes. Over time different models representing the same capabilities at different scales will make up the digital thread, feeding improved knowledge into early stage program development. The creation of a living digital twin and associated models can also lead to designs and updates that better satisfy capability needs, not just requirements, feeding back into government capability assessments.

3.3 SYSTEMIGRAM 3: THE DIGITAL ENGINEERING INFRASTRUCTURE

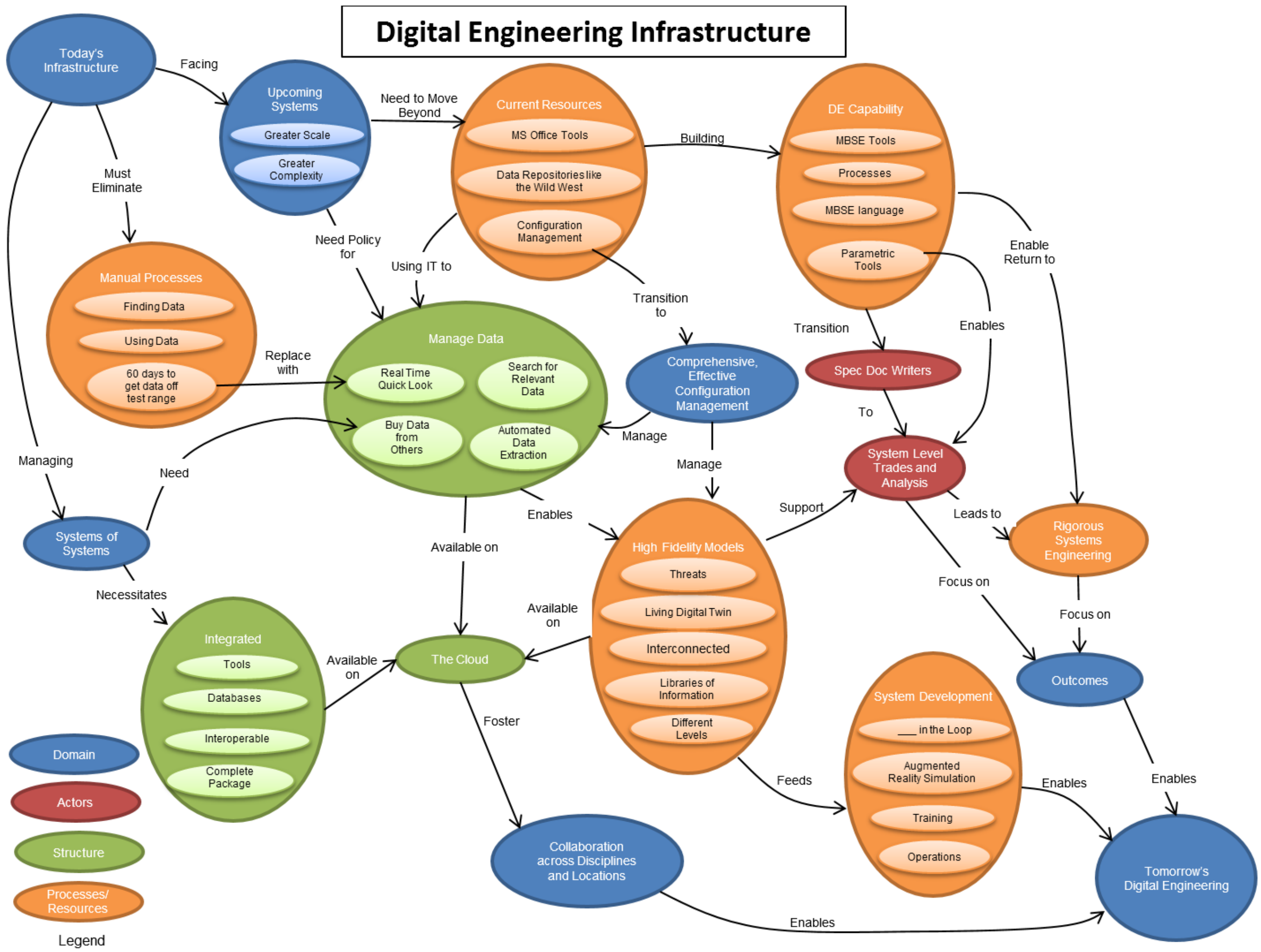

Figure 5. Systemigram 3: Digital Engineering Infrastructure

Today's acquisition engineering infrastructure is challenged by projects of increasing scale and complexity. Engineering work is built upon Microsoft Office tools, which are often inadequate for larger complex programs. Furthermore, data repositories are scattered and inaccessible, with no way to validate the quality or accuracy of their contents. Finding the data is a manual process and formats vary with every data source. Configuration management is essentially an ad hoc and informal process, and most of the time it does not exist at all. It often takes sixty days to get test data from a test range.

Engineers need IT communications and database infrastructure that search across repositories for relevant data, automatically extract the data in a useful form, and provide a real-time quick look at test data while it is still at the range. This will not only require hardware and software tools beyond what is currently installed, it will also require new policy to make data available and standardize access and format. In addition, a comprehensive, effective configuration management system is needed to identify current data and old data, and to establish the pedigree of the data.

This improved infrastructure will enable a substantial and necessary improvement in the quality and fidelity of models that support acquisition engineering. Multi-level models will describe and document the system design at various levels of detail. High fidelity models of the threat will be essential for effective weapon systems. The most significant improvement will likely be the interconnection of all models, wherein results from one analysis can flow seamlessly into another simulation. All of the models will draw on curated libraries of information, enabling updates to propagate immediately across all the engineering models. Digital twins will live amongst the models of test articles and designed components and systems.

These models will be used to support testing, including: software in the loop, hardware in the loop, human in the loop and so on. High fidelity models will support augmented reality simulations of the designed system on the battlefield. The models will continue to be maintained after Initial Operational Capability (IOC) to support training and operations.

Today, the acquisition system is struggling to manage SoS. To do this successfully, it will require integrated tools and databases that support all the subsidiary systems simultaneously. Of course, the DoD does not own complete data rights to all these systems. Therefore, data must be purchased from others to populate the integrated databases. Before the systems can be designed to be interoperable, the tools and databases that support their design must be interoperable. All the interoperable tools and data should be available on the engineer's desktop as a complete package.

To replace current desktops that are centered on Microsoft Office tools and happenstance data sources, we need systems engineers to move to Model-Based Systems Engineering Tools, parametric tools and Digital Engineering processes. Systems engineers should transition from writers of specification documents to decision makers and analysts who conduct system level trade studies and system level analyses. These trades and analyses will be supported by the high-fidelity models supported by curated databases that are configuration managed to stay current with the project.

The data, tools, and models should be available to every engineer who needs them through the cloud. This will enable collaboration across disciplines and across locations. Improvement occurs with desktop tools and capabilities, MBSE and Digital Engineering, and elevation of the role of the systems engineer to analyst and decision maker instead of document manager—all of these factors will enable a return to rigorous systems engineering that focuses on outcomes instead of process. These infrastructure changes will lead to the Digital Engineering environment of tomorrow.

3.4 SYSTEMIGRAM 4: TECHNICAL INNOVATIONS TO IMPROVE ENGINEERING PRACTICE

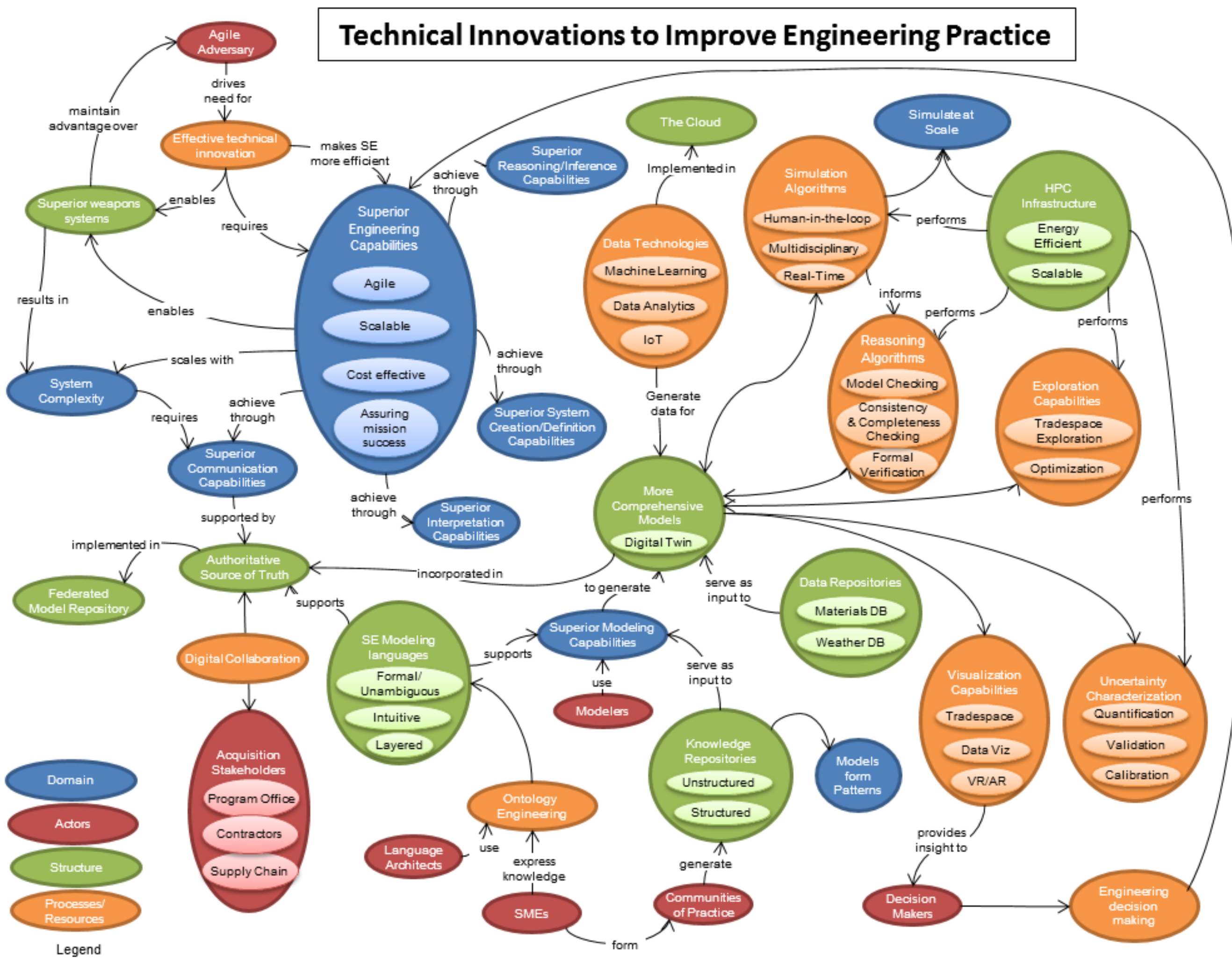

Figure 6. Systemigram 4: Technical Innovations to Improve Engineering Practice

An important aspect of the transformation towards Digital Engineering is the need for Technical Innovation to support and enable improved engineering practices. This need is driven by an agile adversary who continually innovates its capabilities. The US can maintain a strategic advantage over the adversary only by innovating more effectively and creating superior military capabilities. To keep pace with — or preferably outpace — the adversary's rate of innovation, we must invest in the improvement of engineering practices that enable the efficient and effective development of evermore complex military systems. This is where Digital Engineering plays a role—it will allow the US to innovate more effectively by making systems engineering more efficient. It promises to provide superior engineering capabilities that are more agile and scale to larger and more complex systems, capabilities that are cost effective and result in systems that assure mission success.

Superiority in engineering capabilities and practices can be achieved through innovation in several technical areas:

- Communication capabilities,
- Capabilities to support the definition of systems and the creation of models
- Reasoning and inference capabilities, and
- Capabilities to support the interpretation of and decision making based on the analysis results.

These technical areas are discussed in more detail below.

1) *Superior Communication Capabilities:* As military systems become increasingly complex, their successful development involves an increasing number of specialists to cover both the breadth and depth of technical knowledge required. Digital engineering must create superior communication capabilities to allow this large number of stakeholders to communicate efficiently and effectively. At the core of this communication capability is the authoritative source of truth, implemented in a federated model repository. It is through this authoritative source of truth that all the acquisition stakeholders can communicate digitally and maintain a common view on the state of the system throughout its lifecycle. To enable unambiguous communications, the authoritative source of truth requires the support of layered, formal, unambiguous but intuitive systems engineering modeling languages. The development of these languages, in turn, requires language architects and subject-matter experts to collaborate on the engineering of a formal ontology for the systems engineering domain.
2) *Superior Modeling Capabilities:* Besides the development and use of systems engineering languages for communication, the languages need to be supported by superior modeling capabilities (i.e., methods and tools for practicing systems engineers) for the definition and modeling of military systems. Creating these models efficiently and effectively can be achieved by capturing structured and unstructured domain knowledge in knowledge repositories developed by communities of practice. Besides serving as a knowledge retention mechanism, the domain knowledge in the repositories often forms model patterns that can be reused, combined and configured into larger models, significantly improving overall modeling efficiency. Such improved modeling capabilities make it economically feasible to develop more comprehensive and detailed models — an important step towards the concept of a digital twin. In addition to the knowledge repositories, several data repositories also serve as inputs to these comprehensive digital twins.
3) *Superior reasoning and inference capabilities*. In addition to the specification of the system, the digital twin also incorporates analysis results obtained through the use of data technologies, simulations, or other forms of reasoning and inference. Increasingly, simulation models are informed and calibrated by data collected throughout the systems' lifecycles. Tapping into the IoT-capabilities (Internet of Things), combined with data analytics and machine learning, all implemented in the Cloud, allows analysts to generate increasingly accurate, predictive models for design concepts during development, or for specific, individual systems during operation. Increasingly sophisticated simulation algorithms will allow systems to be simulated at scale, from multiple, integrated disciplinary perspectives, potentially in real-time, with humans in the loop. Such large scale simulation are enabled by energy-efficient, scalable high-performance computing (HPC) infrastructure. Besides simulation, HPC also enables other forms of reasoning such as model checking, formal verification, and consistency and completeness checking. Formal verification methods are particularly important in scenarios where simulation is ineffective (e.g., in the case of rare events or adversarial agents). Finally, it is expected that simulation capabilities combined with HPC capabilities will not only be used for final analysis of the selected systems alternative, but for a broad exploration of the tradespace, comparing millions of architectural alternatives in search for the one providing the best system-level tradeoffs.
4) *Superior interpretation capabilities*. A final aspect of a strategy towards improving current engineering practices targets improving the visualization and interpretation of engineering date, and improving its use in support of decision making. To make good decisions about complex engineered systems or corresponding acquisition strategies, decision makers need interactive visualization capabilities for presenting tradespace analysis results or data visualization of detailed engineering, economic and tactical analyses. In addition, to properly take risk into account, uncertainty characterization are needed, based on uncertainty quantification of validated, calibrated models.

The combination of all four areas of technical innovation outlined above will result in improved engineering decision making, superior engineering capabilities, and ultimately, superior weapons systems that maintain our strategic advantage over future adversaries.

3.5 SYSTEMIGRAM 5: CHANGING WORKFORCE AND CULTURE

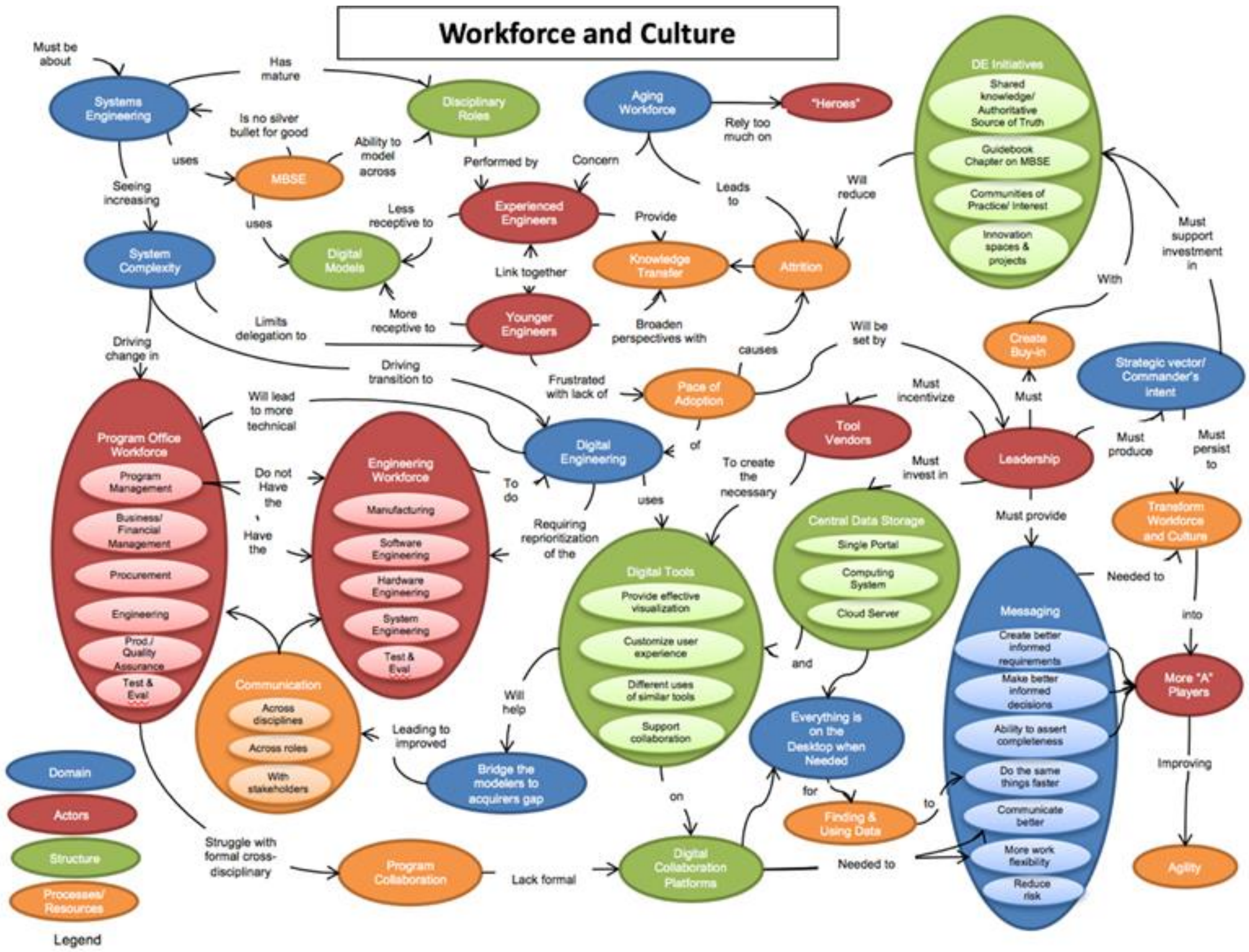

Figure 7. Systemigram 5: Workforce and Culture.

Much of the discussions around digital thread and digital engineering focuses on the technological and modeling aspects. While those are integral to the changing dynamics and processes, often overlooked is the human role and associated changes and how it will shift and might change over time, as the broader system seeks to become more agile.

Most stakeholders and experts do agree there is a cultural change at play, along with needs for the workforce to adapt and change with the broader trends at play as well. There are divergences in perspective in regards to what this might look like, the change in the “old guard” to “new guard”, whether or not there are workforce capabilities and the “talent” will look like. DE is a cultural change in and of itself. There are the new tools which bring in digital natives and will be a merger of new technology and existing experience. As such, the workforce shift will be substantial. There will be big struggles to learn new ways. The goal is having the models to feed the decision processes, which requires training of modelers and a new breed of decision makers. However, it is a challenge to get a large group of people to change. Culture change is not done without resistance or done overnight. There is an extraordinary advantage to maintain the status quo and temptation to “do it like how we did last time”. Culture change is organizationally dependent and unchangeable.

One of the bigger points of diversion amongst stakeholders is whether or not there is a workforce in place to grapple with the changes at play, and if so, whether there are capabilities to address the changes. On the one hand, DE is done today often times without the realization that is being applied. People who do models do it without thinking about it. However, there lacks the process and culture to bring together the emerging digital natives with grizzled veterans and their domain knowledge.

On the other hand, there is the belief that much of the workforce is an aged workforce that looks back at the way things were done rather than looking to the future. The younger group coming in also has shortfalls. The younger workforce is more skilled in a single discipline rather than a broad perspective. There needs to be an effort to better train the younger workforce to oversee multiple different domains to provide a more robust understanding of digital environment. However, bureaucracy and paperwork make it hard to train due to time constraints. Additionally, there is not enough money or time to train older workforce to train them how to use new tools as well.

This squeeze on resources also impacts the focus on SE, as discipline workforces are less and less SE focused and system implications. Labor is expensive and systems are expensive to implement. There are no expectations to think about larger system aspects from the onset. Hiring managers are worried about finding MBSE workers, but there should be more of an effort place finding systems engineers.

This reflects a broader tension between the “old guard” and “new guard”. The steep learning curve and new tools that traditional SE don’t feel comfortable with creates tensions as organizations try to create enhanced capabilities and more agility. Receptivity to modeling is inversely proportional to age. A lot of the innovative stuff is early career - modeling savvy, IT savvy, digital repositories versus paper. These are wired into recent graduates, as such, there will be a gradual aging out process. It is not forced that every engineer be a SysML professional; however, it is encouraged that most at least be a student of it so can speak knowledgeably about adoption. While this is mindful of the “older” generation, the younger generation are frustrated that the move to digital in general is not happening fast enough. This creates a possibility that they might get lost over time. There is a need to instantiate workflow processes - not just the workflow but the policy on the data with it. Still, SE is not about pushing buttons or drawing pretty pictures. A SE should also be a systems thinker, and understand system level analysis and impact. They should be able to understand the broader impact of design changes. It comes down to systems thinking at the end of the day. The key to a good SE, is experience. You can teach someone fundamentals, but you can’t make them one. They need the experience.

Another aspect is that experienced system engineers don’t know how to model, and modelers don’t have system engineer experience. What is the pathway that all system engineers know how to model? There are separate study managers, principle investigators, and modeler roles. Much needs to change before organizations get fully digitized. There are challenges on how to combine the varying skillset levels of the engineers and how to team them up. Need to develop a cadre of modelers who can help stand up MBSE in the projects. We can’t expect all of the SE’s in the physical domain to adopt MBSE.

With DE, digital collaboration is a key enabler. Whether it be communication devices, like smart phones or iPads, or the availability of data with the cloud, there is a distinct ability to integrate data on the cloud. The difference in communications tools is huge and instantly available information. This also helps with collaboration. This will impact the workforce and culture as well. Workforce priorities might change; however, are they grown in house? Do they immediately come in as a system engineer? Is that our next generation of lead systems engineers? SE and SW engineering disciplines will become a key part of the transformation.

If there is a DE environment, what will it look like? Will there be more telework options? For instance, talent could be spread out more evenly, but currently, the government or defense doesn’t have flexible policies for this. In a digital environment, there could be segmented work down into a digital model. DE might make the acquisition workforce more flexible and distributed. Vendors are doing design virtually across multiple teams and locations. This can result in critical cost reduction. If there is some probability of a success with a reduced cost, this is a big win. There will no longer be a need for as many “heroes” working 80 hour weeks and sacrificing their lives for a project or program. This energy and effort can be diverted in other places.

Some organizations support a workforce that employees people to solely understand why we need policy and what is looks like, it drives the paradigm of letting the workforce find out how they use the models and the workforce drives policy so they aren’t over constrained. There are contrasting policy models, some people use policy as checklist and that makes you a good system engineer. While others don’t worry about policy too much and focus on what needs to be produced and do we need all of the products that policy says. Workforce needs to understand which policy to efficiently use. In the policy realm, a special topics chapter on MBSE in the guidebooks would help. Governance is another big piece in this that we need to figure out. Governance is needed at multiple levels. That will have to involve signaling to everyone else.

Overall, in 25 years, SEs will recognize that there are very few problems we haven’t seen before at some level of abstraction. A lot of people think they are the first person to face that problem. Finding the correct abstraction language will let us know what problem we are facing. We are all solving the same problem at the fundamental level. The tools can start to focus on providing templates for problems we have solved before.

3.6 SYSTEMIGRAM 6: A LEXICON FOR EXCHANGE OF DIGITAL ENGINEERING DATA AND MODELS

At the request of the sponsor, a sixth systemigram was created to focus on the digital information exchange process in the emerging digital engineering ecosystem – a known innovation impact area. This systemigram was developed to begin the process of agreement on terminology surrounding the exchange of digital information. The diagram is shown in Figure 8 with the narrative following the figure. All of the components and relationships in this conceptual model were extracted from parts of the initial five systemigrams. However the accompanying narrative is a synthesis of information exchange concepts by the research team and is not a product of the interview and other data collections processes. It provides a good example of the derived artifacts that can be generated from the original systemigram analysis and provides an artifact that can be turned into a formal model such as a Business Process Diagram in future research. This systemigram was presented and validated at a Digital Information Exchange Working Group meeting attended by a broad group of government and industry stakeholders. This is one of a number of different models that can be extracted from the original systemigrams in future work.

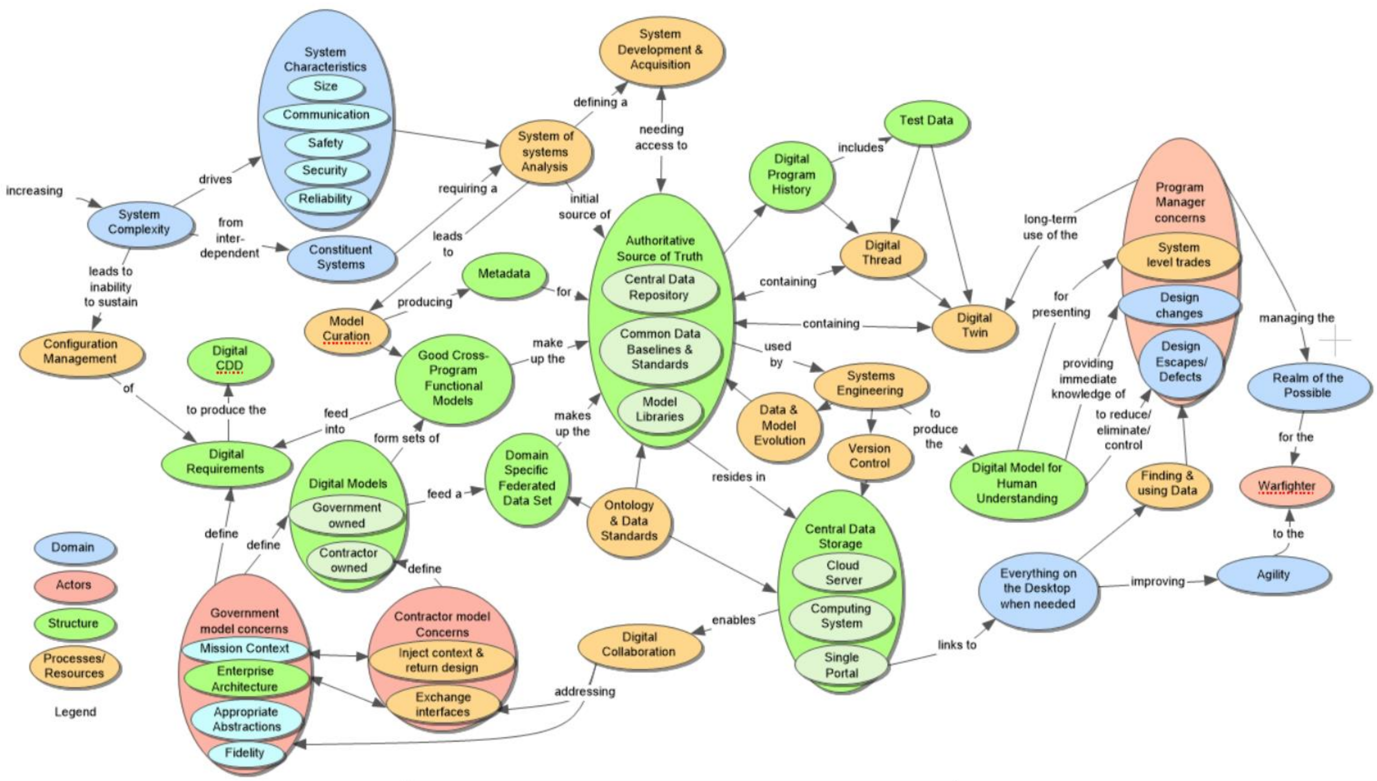

Figure 8. Systemigram diagram of the digital information exchange process.

As with previous diagrams, this story starts with increasing complexity of defense systems. The SoS characteristics and interdependencies with other constituent systems lead to the need for a robust SoS analysis to define the development and acquisition program for a new system. "SoS Analysis" is a new term that reflects the need to digitally analyze the enterprise architecture and concepts of operations for a new system as a complete SoS prior to initial acquisition decisions. Per the interview data this is either a more robust AoA or replaces the current concept of an AoA – either way it implies a new process is needed to address the system and its SoS context that reflects the complexity of new systems.

This SoS analysis will be the responsibility of the system acquirer and will serve as the initial source of data and models for the AST at a program office level. The SoS Analysis will lead to a "model curation" process that produces metadata for and populates the AST. Per other SERC research on model curation [16], one might think of this like curation of artifacts in a museum where "good cross-program functional models" are selected for inclusion in the collection of models that make up the AST. It is important to note that these are functional models, a core systems engineering representation of the system. It is also important to note that the concept of a “good model” in this context be an evolutionary process as program shift to this type of process. The curation of the functional model baseline will address both government and contractor model concerns. A significant learning process in the DE transition will be understanding and normalizing the appropriate abstractions and fidelity of the government data and model set that is provided to the contractor in the acquisition process. There are many issues to be resolved including protection of contractor intellectual property, security, etc. that will be the outcome of the curation process. This initial process will produce the initial requirements baseline for a program, driving formal requirements artifacts such as the CDD (which also needs to be redefined in a transition from paper to model driven requirements).

The government and contractor curation process will determine the government owned and contractor owned digital models that make up the “domain-specific federated data set” that feeds the AST. This also is a new terminology implying the curation is both a domain specific representation of mission and context and also as selected federation of general and domain specific models that are pulled together by the acquisition program office. The core of a successful information exchange model will be the development of both general and domain specific ontologies and data standards that different models and artifacts to interact in the digital domain. The DIEXWG challenge will be the long-term development of these standards.

As previously discussed, the primary role of a future systems engineer will associated with data and model evolution and version control of the curated model federation in the AST. This will be a process that follows the program lifecycle as a digital program history, producing the program decision artifacts that are being called the “digital thread” and the full lifecycle artifact that gets updated with feedback in the fielded system known as the “digital twin.” A poor digital information exchange model will result in an unusable digital thread and twin, highlighting the need for a robust data and model development investment in the early phases of a program – the additional upfront investment will be repaid in cost savings at later program stages.

The outcome of the process that creates the AST is a “digital model for human understanding,” another new concept articulated in the systemigram models. Figure 9 (from the sponsor [16]) depicts generally this concept. The model representation support the program manager decision data concerns of system trades, reduced design escapes/defects, and immediate knowledge of design changes outlined in previous systemigrams. This model outcome will be enabled by an effective digital information exchange that formats and presents everything on the desktop of the decision makers when needed, automating the process of finding and using data, creating more agile decision processes and delivery of new system functions. As discussed in previous systemigrams, the full process should provide a digital baseline to rapidly explore, simulate, prototype, and deploy new functional capabilities to the warfighter that significant advance the realm of the possible in new, innovative capabilities. Figure 9 summarizes the curation process as a “A construct that defines the procedures to select, compile, and analyze digital artifacts to create digital engineering content,” and the digital model for human understanding as “the user interfaces that present digital engineering content and serve the stakeholders’ unique needs.”

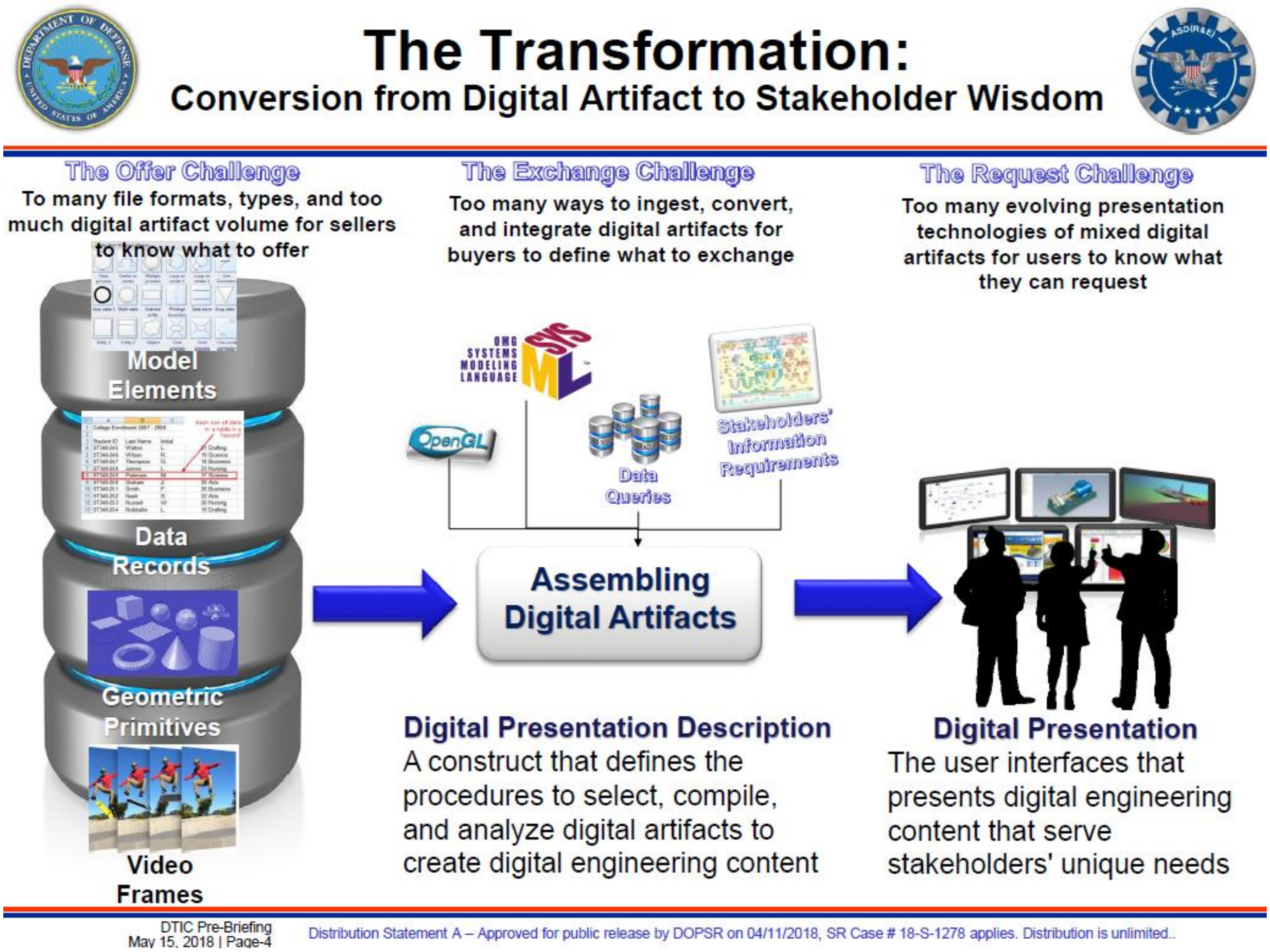

Figure 9. Process representation of a "Digital Model for Human Understanding."

The systemigram diagram in Figure 8 provides a much richer descriptive model of this transformation, allowing much more targeted innovation investment strategies as well as a story that articulates (initially) the value of this transformation. The development of robust digital information exchange models, processes, and decision data will be a make or break process for DE transformation. There is a need to develop both data exchange models and standards, and new roles and processes for model curation and exchange. The DoD strategy must enable the innovation system to step up to this challenge, and remove barriers to success.

4 Stakeholders and Indicators of Change

4.1 Stakeholder Analysis in the DE Strategy

Based on the systemigrams, it becomes clear that the "SoS of interest" in the change process for the acquisition enterprise centers on government program office transformation from standalone and disparate acquisition documents to a new acquisition package baseline defined as data in the AST. This section highlights an initial analysis of key stakeholders in the process, and their needs or values that must be satisfied for successful change. This is based on the breadth of interviews conducted to date, and needs to be augmented in future work on a more thorough review of key actors in the innovation space.

Stakeholder Interviews

The project conducted interviews with 25 individuals across 15 visits. The visits and organizations are listed below but the individuals interviewed will not be published. An important context driver at this point is the limitation on interviewees to government organizations and government related research centers/labs. This creates a limitation in the diversity of the full narrative, but was a strategic choice agreed upon at the program start between the sponsor and research team in order to fully understand the acquisition related boundaries in the systems. Future studies should expand the interviews, facilitations, and narratives to a broader set of stakeholders. This should be done prior to a full innovation system analysis as these perspectives will be key to the innovation system definition.

In addition, the collection of interview narratives is targeted at reaching a diverse set of perspectives and does not attempt to reach all stakeholders or even a formal sample set. Any key stakeholder organizations not listed were either not interviewed due to schedule issues or because the expected interviews would not add new perspectives to the systemigram models. What constitutes "enough" interview data is a judgment call by the research team based on whether or not there are perceived gaps in the systemigram models. These models can be updated by additional interviews in the future.

Although DoD acquisition was the primary focus, the team also interviewed a number of people in the National Aeronautics and Space Administration (NASA) and Jet Propulsion Lab. This was intended to integrate lessons learned from some of their DE pathfinder programs into the narratives. These interviews were consistent with DoD perspectives and helped to fill out the models with additional experience context.

The following organizations participated in the interview process:

- Office of the Deputy Assistant Secretary of Defense for Systems Engineering (DASD/SE)
- Joint Staff Joint Requirements Analysis Division (JRAD J8)
- Secretary of the Air Force/Acquisition (SAF/AQ)
- Army Program Management Office/Aviation (PM-Aviation)
- Office of the Director of Operational Test and Evaluation (DOTE)
- Army Tank and Automotive Research and Development Center (TARDEC)
- Navy Space and Naval Warfare Systems Command (SPAWAR) San Diego
- Air Force Program Office, Ground Based Strategic Deterrent (GBSD)
- Army Program Office, Future Vertical Lift (FVL)
- The Aerospace Corporation
- John Hopkins Applied Physics Laboratory
- NASA Headquarters
- NASA Marshall Space Flight Center
- Jet Propulsion Laboratories (JPL)

In addition the narratives were augmented with published experiences from a number of other pathfinder programs via desk research.

Stakeholder shifts (interview snapshots)

Stakeholder shifts are interview snapshots from the consolidated interview narrative that represent emerging stakeholders of interest or stakeholders who have changing influence or roles in the enterprise. These are noted as narrative statements below.

> "Single engineers can no longer contain a mission in their head. The mission is big enough and complex enough that if we didn't have the single source of truth we could not all be working on one baseline."

> "[DE] has to be about SE, you have to first ask yourself if you're doing SE."

> "A big benefit of the modeling is to stop the SE's from doing accounting (lists) and move them to quality control of the development process. The models create more time for QC."

> "SE and software engineering disciplines will become a key part of the transformation."

> "We do not have a good way/culture to marry the emerging digital natives with grizzled veterans and their domain knowledge."

> "There is tension going on right now between old guard and new guard. Steep learning curve and these are tools that traditional SE don't feel comfortable with… Receptivity to modeling is inversely proportional to age. A lot of the innovative stuff is early career - modeling savvy, IT savvy, digital repositories versus paper. These are wired into recent graduates. There will be an aging out process."

> "[DE} is most about being a good customer. Making sure at the PM level that we were a better informed customer with respect to what we are buying and building."

> "The team followed an onion shell analogy: super users developing the models, managers of the model, and the general SE community at the skin. The general SE community never wrote [models] and seldom used it. The model and modeling tools need to output communication media to all of the general users in a form they are comfortable with."

> "Government configuration management should see a cosmic shift. But CM and data management as it scales is a scary proposition. Need the data and information tools to manage the scale and complexity."

> "System of systems analysis requires you to have data that others have. This will be a big cultural change, government is great at creating data stovepipes. Need policy that manages the central data repository. Looking across our platforms, sometimes we have the data, sometimes the contractor does."

> "It would be nice if the organizational structure was implemented to follow the tool chains. Would organize around standards and standard libraries/data repositories."

> "In the future there are concerns about artificial intelligence (AI) and the interactions of many systems that blend human and AI. Paradigm shift."

> "Technologies that foster collaboration are key."

> "Will need to bridge the modelers to acquirer's gap. Need tools that figure out what data we are going to buy. How do you manage data integration versus budget?"

"Communication across discipline. Especially when you try to get scientists and engineers on the same page since they don't speak the same language. [DE is] a big tool for help bridge those gaps."

"If you don't have buy-in, nothing is going to happen. Need right leaders in place to drive it."

Stakeholder Value Wheel

The stakeholder value wheel, shown in Figure 10, is a simple visualization tool that attempts to list all critical stakeholder types and their primary interest in the change in a single place.

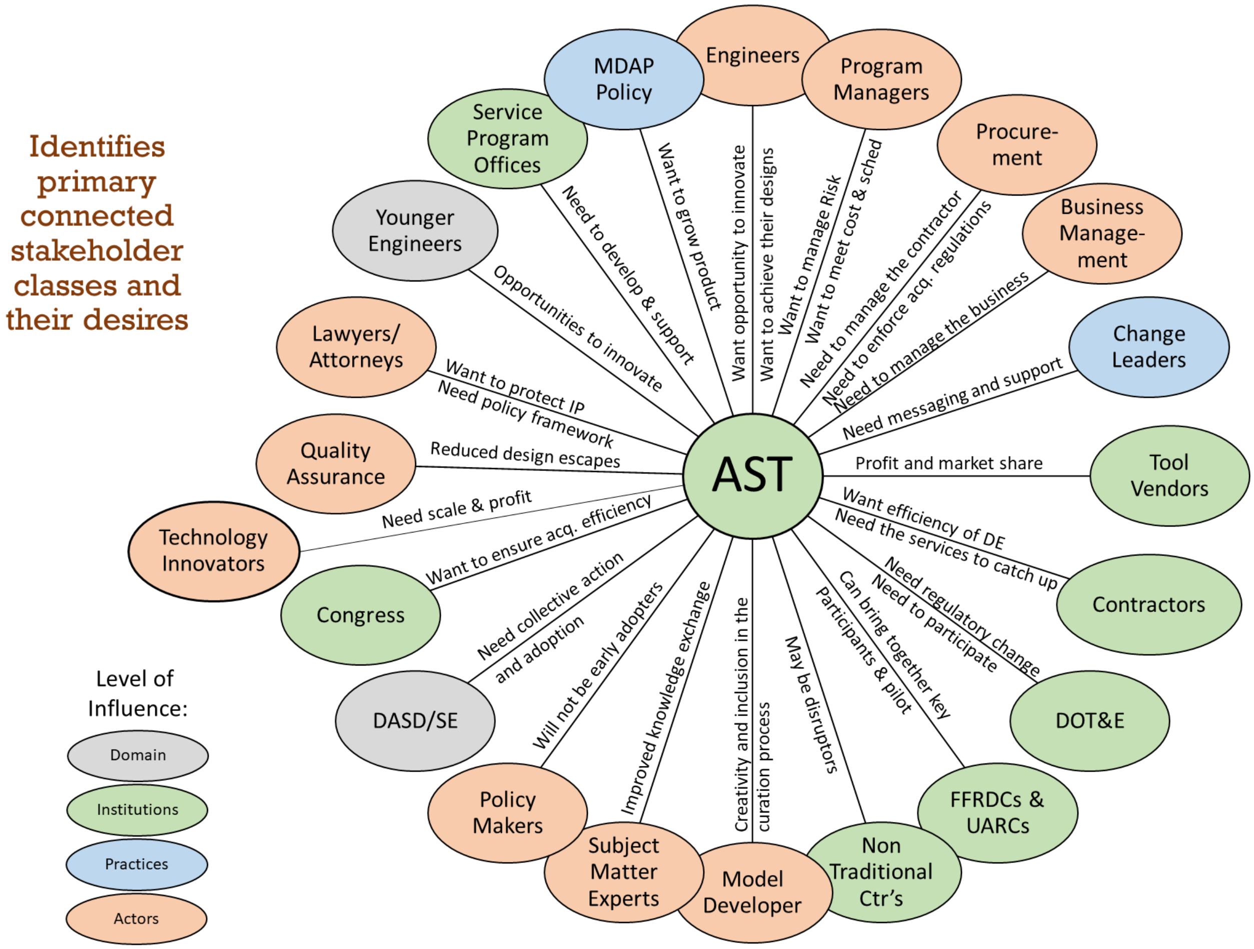

Figure 10. Stakeholder Values Wheel.

Successful transformation will be dependent on meeting or changing the primary needs or values of the key stakeholder groups. This view is presented as an artifact of the interview process at this point. Future model development can more explicitly define their metrics and roles. Key insights extracted from the narrative snapshots and this visualization are as follows:

- There will be a shift in the discipline and roles of systems engineering, primarily shifting their role from quality control of the engineering process to quality control of the engineering design.
- There will be a generation gap as experienced systems engineers, many of whom are not modelers, interact with younger engineers who come in with native digital and modeling experience.
- A role that formalizes the curation of SME knowledge into the AST, and also a role that supports curation of models, will emerge.

- Contractors and their lawyers will have to address ownership and intellectual property concerns with shared government/contractor models. This is a place where non-traditional contractors may play a disruptive role.
- There is a tremendous opportunity for technology innovators to address this transitions, the current generation of systems modeling tools are still in their infancy. Their interest is more likely to be driven by broad industry adoption rather than DoD, as digital engineering evolves a trend to become more prevalent across all industry sectors.
- Change leaders are required to transform the enterprise, primarily at the service program office and contractor product line levels. They will need to be armed with messages that articulate the value and benefits of DE and must persist in the change process.

4.2 Leading and Long-Term Indicators of Change

An analysis of metrics opportunities was developed from the systemigrams. Note that this is a qualitative analysis at this point based on conceptual modeling of the future DE-enabled enterprise. It is intended for discussion. Development of detailed metric recommendations and descriptions would require a more detailed analysis of existing metrics and service acquisition feedback on future metrics.

The systemigram analysis suggests that DE will impact four overall DoD acquisition performance metrics and a large number of program office level metrics. Enterprise acquisition metrics might be characterized as long term indicators of transition success, while the program office metrics contain short- and medium-term indicators. A key to successful enterprise transition is the identification of short-term metrics or “leading indicators of change” that are linked to longer term metrics, as most of the current day stakeholders in the DE strategy will likely have moved on to other roles before the long-term success or failure has been fully realized. In developing a computational and predictive model of the enterprise transformation, it will be important to identify an appropriate set of leading indicators to simulate and analyze so that meaningful predictions can be evaluated with early results. The metrics determined from the systemigrams are summarized below (in no particular order).

A. Enterprise acquisition metrics

1. Average MDAP contract length, MS B to IOC. Annual reports of defense top level metrics indicate that the average MDAP contract length from Milestone B to IOC has increased from 4 years to 7 years since 2004. The most cited reason for this is increased system complexity. Since DE initiatives are mostly in response to complexity, the gradual incorporation of DE-driven acquisition should reverse the trend in this metric. Reasons that could be tracked include improved upfront systems-of-systems analysis leading to increased operational simulation at scale, program decisions increasingly using data to drive decision-making, and reduced time to find and access data.
2. Post MS B requirements stability. 33% of program performance issues that drive Nunn-McCurdy cost breaches are attributed to instability of program requirements post-milestone B. This should improve with DE as requirements baselines move from documents to models and pre-MS B simulation of requirements increases.
3. Program reliability metrics. Weapon system reliability and availability metrics that relate to program design escapes should decrease with DE.
4. Acquisition professional certifications. DE will require new certifications for acquisition professionals. Top-level metrics of DE certification need to be developed.

B. Workforce metrics

1. DE will require more STEM capable professionals. The digital transformation will produce a need for more “data savvy” engineers, and possibly lead to a trend that reduces the average age of the DoD engineering

workforce. It will be important to track attrition metrics across the STEM labor categories to ensure that these younger professional can be retained.

2. A goal of DE is to increase the number of “A-players” in the workforce. How to define and measure this? (A research project in itself).

C. Technical data

1. When program decisions are data driven, procuring tech data should shift from a separate acquisition decision process to one that is integral to the SE process. How should this be measured?
2. “Redefining CM” was a continually stated outcome of DE, how to measure this? A change is CM plans or procedures, or a change the CM content of SEMPs might be an indicator.

D. DE initiatives

1. Metric: PMO pace of adoption of the DE strategy.
2. Metric: Number of PMO DE initiatives.
3. DE will create digital repositories of program history. Metric: Number of programs having a digital twin.
4. Metric: Number of program best practices developed in DE methods/processes/tools.
5. Metric: Number of service/program DE Communities of Practice.

E. Authoritative Source of Truth (AST)

1. Metric: Number of program office data repositories.
2. Metric: Number of programs using digital collaboration platforms.
3. Metric: Number of repositories or platforms identified as AST
4. Metric: Number of models under AST control
5. Metric: Number of data sets under AST control
6. Metric: Number of models under AST control per program
7. Metric: Number of models under AST control per phase (for example, TMRR or EMD) – this could be a leading indicator if many models start showing up in pre-milestone A phase, suggesting new programs are adopting DE
8. Metric: Number of times ASTs are accessed. Could track accesses to use models or data versus accesses to write / create / modify models or data
9. Metric: Number of reviews that are run off AST-controlled models and data
10. Metric: Number of field tests or range tests that use models or data sets drawn from an AST
11. Metric: Number of field tests or range tests that load test results into an AST
12. Metric: Number of ASTs that have individual configuration control procedures
13. Metric: Average number of approvals required to create or modify a model of data set in an AST
14. Metric: Average number of individuals who have access to a model in an AST, per model

F. Systems Engineering Processes.

1. DE will redefine developmental and operational test practices from requirements validation toward model validation goals. How will test data availability be measured in this transformation?
2. DE and associated MOSA initiatives will improve modular interaction of systems and new technology insertion. How will this be measured?
3. DE and associated MOSA initiatives will increase competitive awards and potentially small business awards for subsystems and tech insertion. How will this be measured?
4. DE will gradually eliminate manual processes, leading to more automation and increased business process efficiency. There are a number of metrics that could be defined here. The systemigrams did not produce any lower level concepts in this area. Detailed analysis of these would need to be a separate project.
5. Metric: number of high fidelity models used in program trades.
6. Metric: number of digital ICD and CDD documents.
7. Immediate knowledge of design changes between the contractor and program offices will change decision making in program management. It should decrease the overall change board metrics related to time and accuracy of change approvals.

8. Overall knowledge of the design will decrease the time and improve the accuracy of the SETR process. There are a number of SETR metrics that will be impacted by DE. The NAVAIR model-centric engineering pathfinder should provide insight into these.

G. Technical Innovations

1. Metric: number of programs using government HPC assets.
2. Metric: number of tools created specifically to examine or use models or data sets in an authoritative source of truth
3. Metric: number of tools put in service to index, manage, or configuration-manage an AST
4. Metric: number of data analytics tools used directly to support or analyze AST models and data

H. Other Acquisition process

1. The DoD capability assessment processes should over time transition to government truth data warehouses. This will change the data and decision making in the DOTMLPF process for new acquisitions. How to measure this?
2. DE should produce a shift in RDT&E costs toward pre-milestone B activities. How to measure this?
3. DE should reduce the time from service identification of threat driven capability needs (Integrated Priorities List) and Urgent Needs to the delivery of solutions.
4. DE should increase the number of representative prototypes developed in the acquisition process.

5 Recommendations and Next Steps

This report is a snapshot in the midst of a long period of enterprise change. The systemigrams created reflect one future state out of many, but one that in the combined narrative of the experts interviewed represents the most effective strategy and outcomes to follow. One might try and describe the completion of the DE transformation in simple terms like “paper artifacts are no longer used” but in truth these artifacts may never go away and the actual transition is a much more complex process with many large and small shifts. The value of the systemigram tool is it moves the description of that possible future from a slide deck or bulleted list into a rich model that captures the key relationships in the transition. Although the primary goal of this project was to produce these systemigrams, their real value will be if they continue to inform other discussions and projections, evolve the strategy, and inform wise investments and other decisions that move the change along. The artifacts in section 5 represent just a few of the additional insights that come from the original efforts.

Key Findings

1. The transformation to digital engineering envisioned by OSD’s Digital Engineering Strategy is underway. Hard evidence for this was seen throughout the interviews. DoD leadership is solidly behind the transition at the top and we found evidence of that leadership across every level of the DoD command structure. However, the number of programs embracing DE is still quite small in relation to the scale of the enterprise.
2. Numerous pathfinder efforts across NASA and the DoD are informing both the technical path and the policy and economic drivers of this change. The DoD leadership must exercise patience and apply continuous change leadership as many more pathfinders will be needed to mature the strategy. A key aspect of the workforce and cultural shift is the messaging that comes from DoD leadership on the value of DE – this must be developed and applied consistently across program offices.
3. Digital engineering is perceived by the broad community interviewed in this task in a way that naturally aligns with the five goals in OSD’s Digital Engineering Strategy.
4. The infrastructure is primarily in place to support the transition, although the shift to “engineering in the cloud” will be opposed by many in the enterprise. This is a shift that is already happening broadly in the software community with DEVOPS practices and enterprise “software factories” so it will be wise to track and reuse their lessons learned.
5. There are many gaps between what is currently available in technology and processes versus what will be needed to implement digital engineering, particularly in the management of models within the Authoritative Source of Truth. This includes rigorous processes for verifying, validating and accrediting models, and distinguishing between representations of intended designs, expected performance, and current status. This also includes means for protecting the intellectual property of the model owners and the security of the models. Significant innovation is needed. Pathfinders are underway across not just defense/aerospace but also many commercial enterprises so the DoD will not need to do everything.
6. People do what we measure so the development of good metrics that reflect the leading indicators of change, primarily at the service program office level, are much needed.

Recommendations

1. **Metrics.** In order to measure progress toward an enterprise wide transformation, the appropriate measurement models should be identified and developed. A methodology for tracking these measurements

should be put in place. The work on RT-182 identified a number of possible metrics for initial discussion with the service level acquisition professionals. Next steps in this work are to fully define the measurement approach and expected outcomes.

2. **Model Curation and Credibility.** A rigorous approach should be developed to verify, validate, and accredit the models that are incorporated into the Authoritative Source of Truth. Government and industry personnel who use the Authoritative Source of Truth will need to know the quality of each model and the range of data over which each model can be trusted. The process that curates, manages, and governs the models must also be addressed in the near future.
3. **AST Metadata.** A standards process should be initiated to standardize metadata for the models and data that will be incorporated into the Authoritative Source of Truth. Metadata should identify the degree of accreditation and range of validity of models in the AST. Metadata should distinguish between data and models that describe requirements (the intended design), design status (the performance of the design if it were implemented today), and the expected performance of the design when it reaches initial operational capability. There are doubtless other important metadata functions beyond those listed here. The retail and service industries have made huge strides in this area with web3.0 standards and ontologies, follow their lead.
4. **Innovation.** The enterprise is evolving incrementally but there is also acknowledgement that significant process and technology breakthroughs will be needed to fully achieve the goals of the DE strategy. The DoD should use all tools they have to encourage breakthrough innovation in this area. This will be difficult as DE is a support activity and not a technology that directly affects the fight. A tolerance for creativity and safe experimentation, completions of innovation impact studies and roadmapping, and investment in methods, processes and tools must be sustained.
5. **Human Capital.** This will be a significant shift in the workplace. “Data driven acquisition” will be more natural to the “digital natives” who are entering the workforce. Still, care must be taken to engage the experienced engineers and acquisition professionals. Training programs must evolve with the strategy.

Next Steps

The successful transition in a broad sense will center on the concept of the authoritative source of truth and how the service level program offices adopt and use this construct. Further analysis is needed to capture and define the guidance at this level. One might use the mental model of “A Program Office Guide to Successful Transition” to describe this. A phase 2 facilitation that engages with select program offices adopting DE and engages a broad swath of industry (contractors, other commercial experience, tool vendors, etc.) is needed. This engagement should be focused on development of a solid metrics foundation for measuring the enterprise change process and its successes and failures. A phase 2 effort should also complete the innovation system analysis and build a strategy to address enablers and barriers to change.

Further efforts are needed to engage and define how the early and late stage ends of the acquisition community adopt and benefit from DE - these are the capabilities assessment and development, operational, and test functions. These groups are not currently engaged in the strategy but will be critical to its success. Investment in pathfinders and strategy development must also be sponsored in these functions. The return on investment in DE will not be as much in the development process as it will be in the capability to needs arena (speed) and test (reduced design escapes). This cycle is repeated continuously in the sustainment phases of the lifecycle and large returns can be expected as the capabilities analysis adopts more model-driven practices (simulate before spending) and the test community operates continuously out of and into the authoritative source of truth.

As the transition proceeds new uses for DE and new benefits from the process will accrue. A sustained program that encourages exploring the art of the possible and understanding of the unique use cases that will evolve should be pursued. The outcome of this work should be dissemination of the lessons learned and an increase in the number and speed of the cycles of learning in this domain. This is happening today through mostly informal methods, the communication of these should be formalized, communities of practice encouraged, and forums for exchanging knowledge supported.

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6 Abbreviations and Acronyms

AoA	Analysis of Alternatives
AI	Artificial intelligence
ASD	Assistant Secretary of Defense
AST	Authoritative Source of Truth
CDD	Capability Definition Document
CM	Configuration management
CONOPS	Concept of Operations
DASD/SE	Deputy Secretary of Defense for Systems Engineering
DE	Digital engineering
DoD	Department of Defense
ESoS	Enterprise Systems of Systems
FFRDC	Federally Funded Research and Development Center
FMECA	Failure Modes, Effects, and Criticality Analysis
HPC	High Performance Computing
ICD	Initial Capabilities Document
INCOSE	International Council on Systems Engineering
IOC	Initial Operational Capability
IRB	Institutional Review Board
IT	Information technology
JPL	Jet Propulsion Laboratory
MBSE	Model-based systems engineering
MDAP	Major Development and Acquisition Program
MOSA	Modular open systems approach
NASA	National Aeronautics and Space Administration
PM	Program Manager
PMO	Program Management Office
QC	Quality control
SERC	Systems Engineering Research Center
SoS	System of Systems
SE	Systems engineering
SETR	Systems engineering technical review
SME	Subject Matter Expert
STEM	Science, technology, engineering, and mathematics
SysML	System Modeling Language
UARC	University Affiliated Research Center

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