SYSTEMS ENGINEERING RESEARCH CENTER

Summary Report

Task Order WRT-1001: Digital Engineering Metrics

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Principal Investigator: Tom McDermott, Stevens Institute of Technology

Co-Principal Investigator: Eileen Van Aken, Virginia Tech

Research Team:

Stevens: Nicole Hutchison, Mark Blackburn, Megan Clifford, Zhongyuan Yu, Neal Chen

Virginia Tech: Alejandro Salado, Kaitlin Henderson

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INTRODUCTION

The DoD Digital Engineering (DE) strategy[1] outlines five strategic goals for 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."

DE is defined as ''an integrated digital approach that uses authoritative sources of systems' data and models as a continuum across disciplines to support lifecycle activities from concept through disposal. A DE ecosystem is an interconnected infrastructure, environment, and methodology that enables the exchange of digital artifacts from an authoritative source of truth."[2] Model-Based Systems Engineering (MBSE) is a subset of DE, defined as "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."[3] MBSE has been a popular topic in the SE community for over a decade, but the level of movement toward broad implementation has not always been clear. With the release of the DoD DE Strategy, a clear set of high-level goals are defined for the DoD acquisition community and its industry base. The terms DE and MBSE are used interchangeably throughout this report.

Digital transformation is a change process heavily rooted in "how we train and shape the workforce to use those processes", as noted by Goal 5 of the DoD Digital Engineering Strategy. Each of the DoD's goals implies that an enterprise, organizational unit, or multi-organizational program has a means to define the outcomes of a DE strategy, performance metrics, measurement approaches, and leading indicators of change in the transformation process. This research sought to define a comprehensive framework for DE benefits and expected value linked to the ongoing development of DE enterprise capabilities and experienced transformation "pain points," enablers, obstacles, and change strategies.

A key result of this research is the development and definition of two frameworks that categorize DE benefits and adoption strategies that can be universally applied to a formal enterprise change strategy and associated performance measurement activities. The first framework is linked to the benefits of DE and categorizes 48 benefit areas linked to four digital transformation outcome areas: quality, velocity/agility, user experience, and knowledge transfer. This framework identifies a number of candidate success metrics. A test application to an ongoing DoD pilot project was completed and is documented in this report. The second framework addresses enterprise adoption of DE and provides a categorization of 37 success factors linked to organizational management subsystems encompassing leadership, communication, strategy and vision, resources, workforce, change strategy and processes, customers, measurement and data, workforce, organization DE processes relate to DE, and the organizational and external environments.

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[1] Department of Defense. 2018. Digital Engineering Strategy. Washington, DC: US Department of Defense. June 2018.
[2] Office of the Deputy Assistant Secretary of Defense (Systems Engineering) [ODASD (SE)], "DAU Glossary: Digital Engineering," Defense Acquisition University (DAU), 2017.
[3] Systems Engineering Vision 2025 Project Team of INCOSE, "A World in Motion - Systems Engineering Vision 2025," International Council of Systems Engineering (INCOSE), San Diego, CA, 2014.

ENTERPRISE METRICS CATEGORIZATION

Digital engineering is a subset of the larger aspects of enterprise digital transformation. Gartner[4] reported four common characteristics for good enterprise level digital transformation metrics: *adoption*, *usability*, *productivity*, and *new value*. This research developed five metrics areas relevant to DE: **adoption**, **user experience** (*usability*), **velocity/agility** (*productivity*), **quality** and **knowledge transfer** (*both new value*).

A DE transformation process needs to assess both **adoption** of the methods and tools into the workforce in terms of number of users, resources, etc., and also the drivers of adoption that are linked to **user experience** with the methods and tools. To understand *productivity* indicators and areas of *new value*, the previous SERC study, Enterprise System-of-Systems Model for Digital Thread Enabled Acquisition, was used as the base digital enterprise transformation model.[5] This study linked digital enterprise transformation to outcomes related to improved **quality**, improved **velocity/agility**, and better **knowledge transfer**. Knowledge transfer is a unique value of DE/MBSE that can be distinguished from other digital enterprise transformation metrics. A primary goal of MBSE and the associated data collected in an Authoritative Source of Truth (ASOT) is communication, sharing, and management of data, information, and knowledge. Based upon this background research, we created a general categorization of DE/MBSE organizational change metrics linked to quality, velocity/agility, user experience, knowledge transfer, and adoption. Using literature reviews and a broad survey of DE/MBSE benefits, obstacles, and enablers, as well as government and industry discussions, the research produced an initial “top-10” list of metrics described in Table 1.

It is important to note that measurement of DE/MBSE is a complex process that must be integrated with the entirety of enterprise measurement strategies across all enterprise functions. DE/MBSE cannot be isolated to a small group or limited set of programs if the goal is to understand and track enterprise value. Generally pilot efforts are recommended to start the adoption process, but maturity in DE/MBSE must become enterprise strategy and a component of enterprise performance measurement. This list is a starting point, a full list of 55 metrics categories derived from the research is provided later in the report.

Table 1. Top-10 collected enterprise metric definitions.

Metric Area	Metrics Category	Inputs	Ex. Processes	Ex. Outputs	Outcomes
Quality	Increased traceability	User needs and system requirements are in a modeling tool and linked to truth data & models	• MBSE: reqs., structure, use cases, traceability tools • ASOT: all reqs. at each level are linked with data	• Decreasing number of reqs. changes • Improving requirement volatility trends	• Fully digital traceability of reqs., design, test, and information • Available from one source of truth

[4] https://www.gartner.com/smarterwithgartner/how-to-measure-digital-transformation-progress/
[5] Systems Engineering Research Center, Technical Report SERC-2018-TR-109, Enterprise System-of-Systems Model for Digital Thread Enabled Acquisition, July 13, 2018.

Metric Area	Metrics Category	Inputs	Ex. Processes	Ex. Outputs	Outcomes
Quality	Reduced defects/errors	Data, models, reqs., design artifacts	• Peer review and technical review in models • Design automation • Test automation	• Defects/errors discovered and corrected earlier in development phases • Less total defects/ errors • Error-free deployments	• Reduced total errors/defects in each program phase • Reduced errors/defects that escape from one phase to the next • Increased number of saves in each phase
Velocity/ Agility	Reduced time	Historical estimated effort, planned effort, resourced schedules, milestone schedules	• Estimation processes: COCOMO, COSYSMO, etc. • Schedule tracking or EVMS	Program schedule durations trending toward reduced total or activity times	Time reduction trend data: • total project schedule • average across projects • total and average per activity • response time to need • delays from plan
	Improved consistency	Planning schedules and resource loading, prioritization of needs, development and delivery processes, and stable resources	More regular and frequent development and implementation planning periods	• More predictable scope and cycle time for capability releases • More consistent content and schedule for production deployments	• Processes produce consistent results from project to project • Data or models have consistent use from project to project • Practitioners apply consistent work processes and instructions
	Increased capacity for reuse	Standards, data, models, search tools, CM tools, certifications, data/model managers	• Data and functional modeling • Patterns • Standards • CM • Compliance testing	• Pay once for data = reuse everywhere • Standard reusable capabilities or sub-functions • Compliance	•Models/ datasets reused project to project • Percent direct use/ modification/ change • Related cost/ schedule estimation and actuals

Metric Area	Metrics Category	Inputs	Ex. Processes	Ex. Outputs	Outcomes
User Experience	Higher level support for automation	Investment resources for automation, data collection, and automation tools	Automated: • document generation • test • data search, etc.	• New processes • Reduced labor hours • Reduced time	• Automated v. manual activities • Investment in automation • Automation strategy
Knowledge Transfer	Better communication/ info sharing	Investment resources for collaboration and communication tools, IT infrastructure, and data and libraries	• Teams interact around shared data • Participation in model-based reviews • Data/model desktop availability	• Number of employees and disciplines communicating and sharing information • Number of events held in the toolsets	• Processes and tools to share and jointly assess information • Opportunities to share knowledge and learn in process around common tools and representations
Adoption	DE/MBSE methods and processes	Enterprise strategy and investment, experience with DE/MBSE	• Periodic assessment via survey and scoring	• Attainment of "level 4" capabilities	Availability and maturity of MBSE capabilities (*refer to the INCOSE MBSE Capabilities Matrix[6] for a full assessment*)
	Training	Curricula, classes, mentoring, assessment	• Training • Learning management	• Availability of training • Investment in training • Number trained • Effectiveness of training	Appropriately trained and experienced workforce and customer
	Increased willingness to use DE/MBSE tools	Vision/mission, leadership support, incentives, tools, methods/ processes, training	• Change management strategy	Number of: • people actively using the tools • tool experts • people actively working with tool artifacts	Models and tools produce communication media to all general users in an accessible form

[6] INCOSE Model-Based Enterprise Capability Matrix and User's Guide, Version 1.0, January 2020.

APPLICATION OF DE METRICS

DE/MBSE is recommended to be part of an overall digital transformation. DE is part of a broader DoD-wide SE transformation strategy to prioritize speed of delivery, continuous adaptation, and frequent modular upgrades[7]. Discussions with DoD program offices identified five integrated implementation strategies for overall SE transformation: DE/MBSE, Agile/DevOps methods, modular open systems approaches (MOSA), extended use of modeling & simulation at all program phases, and increased engineering rigor through design space exploration[8]. There is implied an underlying transformation of DoD acquisition workforce and culture away from document-based processes toward more integrated model-driven artifacts, and away from large waterfall-driven acquisition strategies toward more agile incremental capability developments.

To be successful, the SE transformation must be integrated across all five DE transformation areas. Two major transformations will significantly change the DoD acquisition approach: elimination of standalone documents toward "everything in the model," and a shift in capability planning to continuous development and deployment approaches. In the long-term, these two transformations will have a significant impact on everything from acquisition workforce and culture to how programs are funded.

In discussions with DoD program offices, we found a link between DE/MBSE implementation and incorporation of Agile software development and DevOps-based deployment strategies. Reducing cycle time and increasing consistency in ability to successfully deploy capabilities provides an overarching measurement theme. DE/MBSE has the opportunity to significantly reduce waste in development and deployment processes via data – all stakeholders continuously work from the same set of data and gradually increase the levels of automation in data-driven processes. As with the DevOps transformation in the software and information technology communities, automation will become a primary input measure and predictability and consistency of product deployments will be a central outcome measure.

As part of the research, the team completed an example linking the DE benefits framework and associated metrics to a DoD pilot effort. This research leveraged another ongoing SERC project, Model Centric Engineering, and specifically looked to correlating DE benefit categories with lessons learned benefits observed during the project. The pilot effort applied DE methods and tools using an ASOT by creating models for everything to demonstrate the art-of-the-possible. The analysis discussed herein performed a correlated rating from 17 lesson learned categories to 22 DE benefit areas grouped into the five metrics areas (quality, agility/velocity, user experience, knowledge transfer, and adoption).

The NAVAIR Systems Engineering Transformation (SET) under SERC Research Tasks RT-157/170/195 and WRT-1008 focused on applying DE methods and tools in a collaborative DE environment to demonstrate a new operational paradigm for government and industry based on a SET Framework defined by leadership at the Naval Air Systems Command's (NAVAIR) [9]. We used the lessons learned in this analysis because they directly rely on DE practices, methods, models, and tools that should enable efficiencies and contribute to productivity. The DE approach integrated methods and tools with enabling technologies:

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[7] Zimmerman, P. Digital Engineering Strategy & Implementation Status, National Defense Industries Association, June 2019.
[8] Summary based on discussions with several DoD program offices.
[9] Blackburn, M. R., M. A. Bone, J. Dzielski, B. Kruse, R. Peak, S. Edwards, A. Baker, M. Ballard, M. Austin, M. Coelho, Transforming Systems Engineering through Model-Centric Engineering, Research Task-195 (NAVAIR), Final Technical Report SERC-2019-TR-103, May 28, 2019.

specifically, a Collaborative DE Environment supporting an ASOT not just for the Government but also for the contractor. It also required the use of DEE technology features (e.g., Project Usage, automated Document Generation, Model View Editors, and Digital Signoffs) and methods to accomplish those lessons learned. The efforts demonstrated a means for a new operational paradigm to work directly and continuously in a collaborative digital environment to transform, for example, how Contract Data Requirement List (CDRLs) can be subsumed into the modeling process using Digital Signoff directly in the model that is accessed through DE.

Initial Surrogate Pilot experiments provide examples demonstrating the art-of-the-possible for many of the cross-cutting objectives of DE, including integrating different model types with simulations, surrogates, systems and components at different levels of abstraction and fidelity, and providing an enduring ASOT across disciplines throughout the lifecycle. The surrogate experiments “modeled everything” in order to show that the concept was possible. The team demonstrated the feasibility of using modeling methods at the mission and systems levels, and also demonstrated the use of models for the request for proposal (RFP), statement of work, and source selection technical evaluation. The Phase 1 surrogate contractor RFP response models link to the government mission and system models. The surrogate contractor RFP response models include multi-physics analyses and early design models that illustrate the potential to have deep insight into the design of a proposed air vehicle system prior to contract award. The use of digital signoff directly in the model provides evidence of a new approach for transforming traditional CDRLs, by documenting and linking digital signoffs with the evidence provided directly in the models. Current efforts are updating an experimental UAV system called Skyzer in the model everything approach.

QUANTITATIVE METRICS ANALYSIS

The analysis correlated 17 categories of lessons learned derived from the NAVAIR surrogate pilots to the DE/MBSE metrics categories: Quality, Velocity/ Agility, User Experience, Knowledge Transfer, and Adoption (listed as “other” in the figure). We used a scoring/weight of: blank, three, five, and nine, where 9 has a strong relationship from underlying aspects of the lesson learned/benefits to the benefits categories. We created a total weighting across the benefits categories and similarly for each lesson learned. The highest-ranking DE/MBSE benefit areas across the lessons learned are summarized below. The 5 highest ranked metrics align with 5 of the top-10 metrics in Table 2.

- [Quality] Increased Traceability
- [Velocity/Agility] Improved Consistency
- [User Experience] Higher Level of Support for Automation
- [Knowledge Transfer] Better Communication/Info Sharing
- [Adoption] Quality and maturity of and people willing to use DE/MBSE Tools

As this analysis was developed independently of the literature review and survey results, it provides at least one program validation of the rankings listed in Table 1. Of note in this example, which is more advanced than a number of other DoD acquisition pilots, is the focus on automation. Reducing workload via automation is a key aspect of User Experience in DE/MBSE implementation. Primary lessons learned are:

- It is technically feasible to develop everything as a model
- Modeling must be established and aligned with methods and guidelines
- Establish infrastructures for IME tools and ASOT as early as possible
- Technology enables collaborative capabilities in model centric engineering

Table 2. Correlation Matrix for Lessons Learned and DE/MBSE Benefit Metrics.

	Quality						Velocity/ Agility							User Experience					Knowledge			Other					Total
This analysis is attempting to relate the lessons learned from the Surrogate Pilot to the DE Metrics Categories	Reduce Errors/Defects	Increased Traceability	Improve System Quality	Reduce Risk	Increased Rigor	Reduce Cost	Improved Consistency	Increased Capacity for Reuse	Increased Efficiency	Increased Effectiveness	Comm/Info Sharing	Early V&V	Reduce Time	Support for Automation	Reduce SE Task Burden	Manage Complexity	Increased Productivity	Imp. System Understanding	Better Access. of Info.	Better Knowledge Capture	Imp. System Design	Alignment w/Customer	Support/Commitment	DE/MBSE methods & proc.	DE/MBSE Tools	Workforce Development	
Total	58	108	87	80	95	62	117	77	91	99	111	51	60	111	59	71	91	76	101	90	79	84	62	93	116	77	
Identify objectives for each phase of the pilot				5	5		5	5	5	5	5			5	3	9	5	3	9	9	3	9	9	5	5		109
Manage Versions for Tools Used to Support Migration to New Toolsets	3	3	4		3	3	9	3	5	5	5	3	5	9	3	3	5		3			5	5	5	9	3	101
Establish infrastructures for IME tools and AST as early as possible	3	9	9	5	5	3	9	5	5	5	9	5	5	9	5	5	9	5	9	3	9	5	5	3	9		153
Technically feasible to develop everything as a model	5	9	9	5	9	3	9	5	5	5	9	3	5	9	5	5	5	9	9	5	9	3	3	5	9	3	160
Establish model management practices early	3	5	5	3	5	5	9	5	5	5	3	3	3	3	3	5	5	5	5	3	5	9	5	9	9	5	130
Project Usages for Model Modularization	3	9	5	5	9	3	5	5	5	3	9	3		5		5	5	5	5	5	5	3		5	9	3	119
Create View and Viewpoints to provide stakeholder relevant views and leverage Viewpoint libraries	5	5	5	5	9	3	9	9	5	9	5	3	3	9	3	5	5	5	5	5	5	5	3	9	5	5	144
Use Digital Signoffs as a means for evolving from CDRLs	5	9	3	5	5	9	9	5	9	9	5	5	5	9	5	3	5	3	5	5	3	5	5	5	5	5	146
Requirement management can be done directly in models	5	9	5	5	3	3	5	3	5	5	3	3	5	5	3	1	5	3	5	5	1	5		5	5	3	105
Modeling provided a means to simplify SOW with emphasis in providing tool agnostic modeling information	3	3	3	5	5	5	5	3	5	9	3	5	5	3	5	1	5	1	1	9	5	9	5	5	5	3	116
MDAO being applied by Surrogate Contractor	3	3	3	5	5	3	3	3	3	3	5	1	3	9	3	5	5	5	3	5	5			5	3	5	96
Establish and align modeling with methods & guidelines	5	9	9	5	5	5	9	5	5	9	5	5	5	5	5	3	5	5	5	5	9	5	3	9	5	9	154
Leverage social-media technologies for continuous communication to complement modeling in an AST	3	3	3	3	3	3	3	3	5	3	9	3	5	3	3	3	5	5	5	9	5	5	3	3	9	9	116
Surrogate Pilot demonstrated a new operational paradigm for collaboration in AST	3	9	5	5	9	3	9	3	5	5	9		3	9	3	5	5	9	9	9	5	3	3	6	6	9	149
Request for Information (RFI) as models useful to test new operational paradigm	3	5	5	9	5	5	5	5	5	5	9	3		5		3	3	3	5	5		9	9		5	5	
Request for Proposal (RFP) as models is technically feasible (supported using DocGen and providing model as Government Furnished Information)	3	9	9	5	5	3	5	5	5	5	9	3	5	5	5	5	9	5	9	3	5	3	3	5	9	5	142
Technology enables collaborative capabilities in MCE	3	9	5	5	5	3	9	5	9	9	9	3	3	9	5	5	5	5	9	5	5	1	1	9	9	5	150

It is important to note the DE/MBSE are tightly coupled to quality of systems engineering methods and processes and workforce capabilities. However, the digital transformation of SE is much more tightly coupled with technology. The quality and maturity of the DE/MBSE tools, particularly integration of the Collaboration Environment and the ASOT, is critical. There might be some perception that modeling takes longer, but we found that the increased rigor leads to reduced errors/defects, especially cross-domain, or level-to-level (mission to system), because all of the models are linked together (i.e., increased traceability) using enabling technologies. We are also able to render and edit these models in a more "cloud-based" way, as well as are able to improve collaboration and provide better access to information directly in a "cloud-like" way. The models increase rigor using formal standardized languages (MBSE terminology/ontology/libraries), enabling higher level support for automation, and leading to increased productivity and increased efficiencies. These should result in reduced time.

DESCRIPTIVE SUMMARY OF TOP-CITED METRICS AREAS

Table 3 provides a full descriptive summary of 55 candidate metrics derived from the benefit and adoption categories. These are grouped into the five metrics areas of Table 1, and ranked by number of literature or survey citations in each area. The table includes example descriptive phrases of each metrics category developed in textual analysis of the literature and survey data. The table also lists examples of potential outcome metrics for each metrics category.

Table 3. Descriptive summary of top-cited metrics areas.

Metrics Category	Example descriptive phrases	Example outcome metrics
Metric Area: Quality		
Increased traceability	requirements, design, information traceability	• Full digital traceability of requirements, design, test, and information • Availability from one source of truth
Reduce cost	cost effective, cost savings, save money, optimize cost	• Lower total cost compared to similar previous work
Improve system quality	higher quality, quality of design, increased system quality, first time quality, improve SE quality, improve specification quality	• Improved: total quality (roll-up of quality measures); first time quality (deployment success)
Reduce risk	reduce development risk, reduce project risk, lower risk, reduce technology risk, reduced programmatic risk, mitigate risk, reduce design risk, reduce schedule risk, reduce risk in early design decisions	• Risks identified and risk mitigations executed via DE enterprise processes • New risks uncovered by system modeling
Reduce defects/ errors	reduce error rate, earlier error detection, reduction of failure corrections, limit human errors, early detection of issues, detect defects earlier, early detection of errors and omissions, reduced specification defects, reduce defects, remove human sources of errors, reduce requirements defects	• Reduced: total errors/defects in each program phase; errors/defects that escape from one phase to the next • Increased number of saves in each phase
Improved system design	improved design completeness, design process, design integrity, design accuracy, streamline design process, system design maturity, design performance, better design outcomes, clarity of design	• Design outcomes show improvement and the design process is more effective compared to similar programs (rollup measure)
Better requirements generation	requirements definition, streamlining process of requirements generation, requirements elicitation, well-defined set of requirements, multiple methods for requirements characterization, more explicit requirements, improved requirements	• Measurement of requirements quality factors in the DE process: correctness, completeness, clarity, non-ambiguity, testability, etc.
Improved deliverable quality	improve product quality, better engineering products	• Reduced deliverable defects • Improved deliverables acceptance rate

Metrics Category	Example descriptive phrases	Example outcome metrics
Increased effectiveness	effectively perform SE work, improved representation effectiveness, increased effectiveness of model, more effective processes	• Effectiveness of a process is how relevant the output is to the desired objective
Improved risk analysis	earlier/ improved risk identification, identify risk	• Risks identified by phase
Better analysis capability	better analysis of system, tradespace analytics, perform tradeoffs and comparisons between alternative designs, simulation	• Decisions balance cost, schedule, risk, performance, & capabilities • Improved affordability, efficiency & effectiveness of tradespace processes
Strengthened testing	model based test and evaluation, increased testability, improved developmental testing	• Improved: test coverage; automated tests; number of errors found by automation versus manual means; efficiency & effectiveness of test process • Reduced number of defects/ errors in each phase
Increased rigor/ Improved predictive ability	rigorous model, rigorous formalisms, more rigorous data, better predict behavior of system, predict dynamic behavior, predictive analytics	• Increased: level of difficulty/ complexity of project; number of alternatives analyzed; subject matter experts involved • Improved: exhaustiveness of data collection; consistency of analysis processes; predictive links between design & capabilities
More stakeholder involvement	easy way to present view of system to stakeholders, better engage stakeholders, quick answers to stakeholder's questions, share knowledge of system with stakeholders, stakeholder engagement, satisfy stakeholder needs	• Improved: process efficiency & effectiveness for stakeholder involvement in modeling; number of stakeholders contributing; stakeholder access to tools, models, data
Metric Area: Velocity/Agility		
Improved consistency	consistency of info, consistency of model, mitigate inconsistencies, consistent documentation, project activities consistent, data consistency, consistent between system artifacts	• Processes produce consistency from project to project in: results; data; models used; work processes & instructions applied by practitioners
Reduce time	shorter design cycles, time savings, faster time to market, ability to meet schedule, reduce development time, time to search for info reduced, reduce product cycle time, delays reduced	• Time reduction trend data: total project schedule; average across projects; total & average per activity; response time to need; delays from plan

Metrics Category	Example descriptive phrases	Example outcome metrics
Increased capacity for reuse	reusability of models, reuse of info/ designs	• Models/datasets reused project to project • percent direct use/ modification/ change; • related cost/ schedule estimation & actuals
Increased efficiency	efficient system development, higher design efficiency, more efficient product development process	• More efficient process time, resources per unit output, flow • Reduced waste
Increased productivity	gains in productivity	• Effort per unit of production
Reduce rework	reduce rework	• Reduced: number of rework cycles; percent rework; errors causing rework; size of rework effort; technical debt
Early V&V	early verification and/or validation	• Formal testing: credited in earlier phases; done in models and simulation vs. system
Reduce ambiguity	less ambiguous system representation, clarity, streamline content, unambiguous	• Higher levels of specificity; decisions based on data; application of uncertainty quantification methods
Increased uniformity	uniformity	• Application of standards: technical, process, work & effort, etc.
Easy to make changes	easier to make design changes, increased agility in making changes, changes automatically across all items, increased changeability	• Improved ability to: implement changes; change management process automation
Reduce waste	reduce waste, save resources	• Lean processes: waste removal and flow (pull)
Better requirements management	better meet requirements, provide insight into requirements, requirements explicitly associated with components, coordinate changes to requirements	• Process effectiveness demonstrated by how relevant output is to desired objective: # requirements, requirements volatility, requirements satisfaction, etc.
Higher level of support for integration	integration of information, providing a foundation to integrate diverse models, system design integration, support for virtual enterprise/ supply chain integration, integration as you go	• Developmental testing credited in earlier phases; testing done in models and simulation vs. system; reuse of data & models in integration activities
Increased precision	design precision, more precise data, correctness, mitigate redundancies, accuracy	• Six Sigma processes • Reduced standard deviation
Increased flexibility	flexibility in design changes, increase flexibility in which design architectures are considered	• Time- and cost-effective incorporation of: new requirements; sensitivity analysis to change vs. a reference

Metrics Category	Example descriptive phrases	Example outcome metrics
Metric Area: User Experience		
Improved system understanding	reduce misunderstanding, common understanding of system, increased understanding between stakeholders, understanding of domain/ behavior/ system design/ requirements, early model understanding, increased readability, better insight of the problem, coherent	• Assessments from activities such as technical reviews and change processes, standard models or patterns of SE and domain, common understanding of architecture/abstractions (architectural quality/risk assessment), etc.
Better manage complexity	simplify/ reduce complexity, understand/ specify complex systems, manage complex information/ design	• Improved: data/model integration & management; distribute control; empowerment across data/between disciplines; ability to iterate/experiment
Higher level support for automation	automation of design process, automatic generation of system documents, automated model configuration management	• Increased: automated vs. manual activities; investment in automation; automation strategy
Better data management/ capture	representation of data, enhanced ability to capture system design data, manage data	• Improved data management architecture, automation • Reduced technical debt
Better decision making	make early decisions, enables effective decision making, make better informed decisions	• Visualizing different levels of specificity; more decisions based on data and analysis, access to and visualization of data
Reduce burden of SE tasks	reduce complexity of engineering process	• Reduce time spent on or waiting for SE artifacts
Reduce effort	reduce cognitive load, reduction in engineering effort, reduce formal analysis effort, streamline effort of system architecture, reduce work effort, reduce amount of human input in test scoping	• Process efficiency demonstrated by relevancy of output to desired objective: effort per unit of production; total effort vs. similar programs; effort vs. plan
Metric Area: Knowledge Transfer		
Better communication/ info sharing	communication with stakeholders/ team/ designers/ developers/ different engineering disciplines, information sharing, knowledge sharing, exchange of information, knowledge transfer	• Improved: processes and tools to share and jointly assess information; opportunities to share knowledge and learn in process around common tools & representations
Better accessibility of info	Ease of info availability, single source of truth, centralized/ unique/ single source of info, simpler access to info, synthesize info, unified coherent model, one complete model	• Develop: tools that support access to and viewing of data/models; widely shared models; executable models
Improved collaboration	simplify collaboration within team	• Develop: tools that support human collaboration around shared data & models
Better knowledge management/ capture	knowledge capture of process, better information capture, early knowledge capture, more effective knowledge management	• Develop: tools that support wide diversity of information; integration across domains; methods to build and enter knowledge

Metrics Category	Example descriptive phrases	Example outcome metrics
Improved architecture/ Multiple viewpoints of model	help develop unambiguous architecture, rapidly define system architecture, faster architecture maturity, accurate architecture design; shared view of system, more holistic representation of system/ models, dynamically generated system views	• Develop tools that support intuitive structuring of model views, story-telling, interface management
Metric Area: Adoption (Ranked separately from the other 4 metrics areas)		
Leadership support/ Commitment	Demonstrating commitment and general support for MBSE implementation by senior leaders through communication, actions, and priorities	• Demonstrate messaging, awareness of DE/MBSE • Participation in reviews, performance management incentives, succession planning
Workforce knowledge/skills	Developing a workforce with the knowledge, skills, and competencies needed to support MBSE adoption	• Availability and maturity of MBSE competencies (refer to the INCOSE MBSE Capabilities Matrix in the complete report for a full assessment)
DE/MBSE methods and processes	Developing and deploying consistent, systematic, and documented processes for MBSE throughout the relevant parts of the organization, including steps/phases, outputs, and roles/responsibilities	• Availability and maturity of MBSE capabilities (refer to the INCOSE MBSE Capabilities Matrix in the complete report for a full assessment)
Training	Investing in and providing the education/training required to develop the workforce knowledge/skills needed to support MBSE implementation	• Appropriately trained & experienced workforce, and customer
DE/MBSE Tools	Ensuring MBSE tools have sufficient quality, have sufficient maturity, are available, and are common	• Tools: availability, investment in, experience with, and stability
Demonstrating benefits/results	Creating "quick wins" to demonstrate results (benefits and outcomes) from applying MBSE	• Develop DE/MBSE growth strategy, pilot efforts, publications, lessons learned
Change management process design	Defining and implementing a systematic change approach to implement MBSE, with clear actions, timeline, roles, resources needed, staged deployment steps/phases for experimentation (where relevant), and outcomes expected	• Revised and relevant vision, mission, change strategy, engagement plan, feedback plan, etc.
General resources for DE/MBSE implementation	Ensuring financial and other resources are available to support MBSE implementation	• Funding, IT support, training support, Internal R&D, etc.
People willing to use DE/MBSE tools	Willingness and motivation of people in SE roles across organization to use MBSE tools	• Communicate models and modeling tools output to all of the general users in an accessible form
Alignment with customer requirements	Identifying how MBSE adoption supports meeting customer needs and requirements	• Implement: customer engagement plan; customer requirements elicitation; involvement of customer; participation with customer

Metrics Category	Example descriptive phrases	Example outcome metrics
MBSE terminology/ ontology/ libraries	Clearly identifying a common terminology, ontology, and libraries to support MBSE adoption	• Investment in enterprise data development and management, shared libraries, stability of data definition and stores
Champions	Defining and creating the role of champion to use expertise to advocate for and encourage others' use of MBSE	• Create evangelist role, and enlist number of evangelists • Demonstrated leadership support
People in SE roles	Quality of and support from people holding SE roles across the organization	• Defined SE role • Develop plan integrating SE and DE, scope of SE teams/organization, etc.
Communities of Practice	Creating a community of practice within the organization to provide guidance, expertise, and other resources as MBSE is deployed	• Investment in CoP • Established number of participants

Figure 1 provides a full summary of the top DE benefit areas from the literature review and survey conducted in the research on DE benefits. The figure depicts the percentage of literature review papers or survey respondents citing each benefit area. This was used to define the top metric categories related to benefits of DE. Figure 2 provides a summary of the top enablers, obstacles, and areas of change based on survey data. This was used to derive the top metrics categories related to DE adoption.

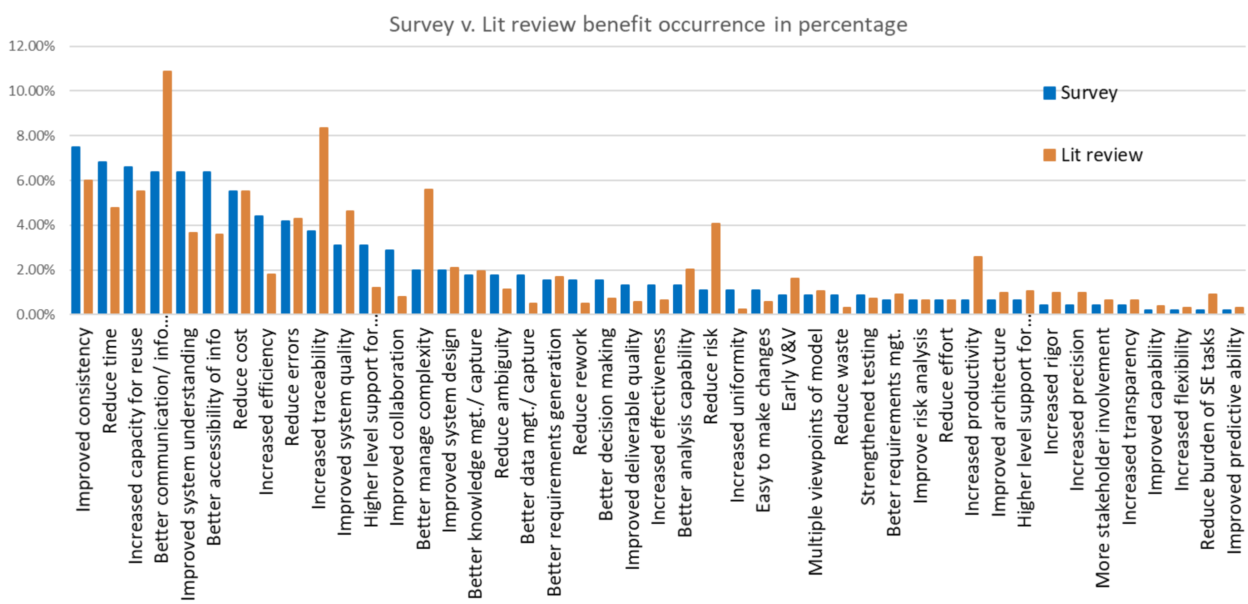

Figure 1. Top Cited DE Benefits Areas from Literature and Survey Results.

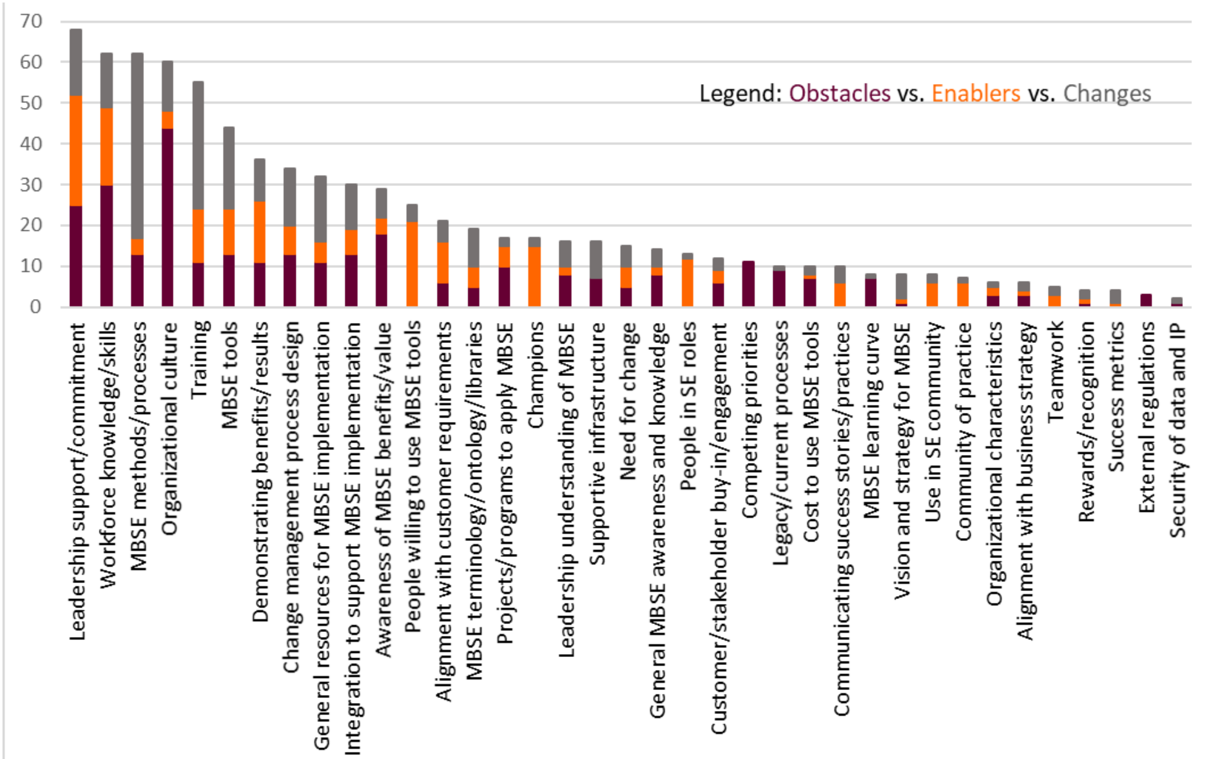

Figure 2. Obstacles, Enablers, and Changes for DE Adoption, ranked by Frequency of Mention.

SUMMARY AND CONCLUSIONS

This research task used the following four guiding questions:

1. What would a "Program Office Guide to Successful DE Transition" look like?
2. How can the value and effectiveness of DE be described and measured?
3. Are there game-changing methods and/or technologies that would make a difference?
4. Can an organizational performance model for DE transformation be described?

At the start of the research effort, the hope was to identify and document best practices across the DoD, defense industry, and other industries related to measurement of the DE enterprise transformation, metrics for success, and standard success guidance. It quickly became clear that best practices do not yet exist in the DE and MBSE community, and the transformation process is not yet mature enough across the community to standardize best practices and success metrics. Given the state of the practice, the research shifted to a set of efforts to define a comprehensive framework for DE benefits and expected value linked to the ongoing development of DE enterprise capabilities and experienced transformation "pain points," enablers, obstacles, and change strategies.

A key result of this research is the development and definition of two frameworks that categorize DE benefits and adoption strategies that can be universally applied to a formal enterprise change strategy and associated performance measurement activities. The first framework is linked to the benefits of DE and categorizes 48 benefit areas linked to four digital transformation outcome areas: quality, velocity/agility, user experience, and knowledge transfer. This framework identifies a number of candidate success metrics. A test application to an ongoing DoD pilot project was completed and is documented in this report. The second framework addresses enterprise adoption of DE and provides a categorization of 37 success factors linked to organizational management subsystems encompassing leadership, communication, strategy and vision, resources, workforce, change strategy and processes, customers, measurement and data, workforce, organization DE processes relate to DE, and the organizational and external environments. The following summarizes the findings based on the four research questions:

What would a "Program Office Guide to Successful DE Transition" look like?
We found that 1) the DE and MBSE communities, across government, industry, and academia, are not sufficiently mature at this point in their DE transformations to standardize on best practices and formal success metrics. Pockets of excellence exist, but experience and maturity vary widely.

We found that 2) Government lags industry in maturity and should look to both their industry partners and the broader swath of commercial industry for best practices. The differing levels of DE capability across a government acquisition enterprise, prime contractors, and support contractors will be an obstacle to successful DE transformation. Programs, particularly legacy programs that have established non-digital processes, must invest effort in program-wide development and maturation of DE.

We found that 3) MBSE and the ASOT, as the core DE strategies for managing the complexity of large complex systems and systems-of-systems (SoS), lag in maturity to other DE strategies, such as Agile software development, Product Line Engineering/Product Lifecycle Management (PLM/PLE), and Integrated Supply Chain Management (ICSM). Pilot efforts that integrate MBSE and the ASOT across other more established disciplinary DE areas are necessary. Lessons learned from these efforts should inform best practices and success metrics for the full DE transformation.

4) We conducted one example pilot to show how full lifecycle DE activities link to a comprehensive metrics framework. Organizations should continue to share lessons learned from their pilot efforts.

5) We believe this research provides the first comprehensive framework to organize best practices and success metrics for DE. The community should share their implementation and measurement strategies, and future surveys should assess maturity and best practices.

6) A "Program Office Guide to Successful DE Transition" is within reach, but more effort is necessary to pilot draft guidance and to test and validate results. Next steps in this research should work with selected program offices to create and execute pilot measurement programs.

How can the value and effectiveness of DE be described and measured?
7) The community perceives significant benefit from DE and MBSE transformation, but specific benefits have not yet been translated to organizational value drivers and success metrics. In fact, organizations appear to be searching for guidance on measuring the value and benefits of DE/MBSE usage. Based on extensive literature review and survey data, this research presents a guiding framework for benefits and metrics. Based on this work, the DoD should provide common guidance to program offices on data collection and should track several top-level measures that are consistently used across those offices. Table 1 of this report makes recommendations based on categories of metrics most frequently reported in literature and from survey data, but further work is needed to evaluate these metrics in practice – few examples exist today.

Are there game-changing methods and/or technologies that would make a difference?
8) Technology in the DE and MBSE ecosystem is evolving rapidly. Tools and infrastructure, based on survey

data, are becoming more mature and less of an obstacle to DE success. However, enterprises must continue to focus on their unique DE innovation strategies to build successful infrastructure and practices, focus resources and people on the unique aspects of the DE infrastructure as part of the DE transformation team (not general IT), and create programs to invest in and evaluate evolving technologies and standards.

9) The transformative aspect of DE/MBSE will succeed based on how technology enables automation of SE tasks and human collaboration across all disciplines across a full model-centric engineering process. The DoD should fund research and incentivize tool vendors to introduce more automation into the DE/MBSE processes.

Can an organizational performance model for DE transformation be described?

10) Successful DE and MBSE are inseparable from good systems engineering. DE/MBSE is just an extension of existing systems engineering roles and skills. DE presents newer roles related to the data science aspects of MBSE, particularly data management, data integration, and data analysis. Also, there is more emphasis on tool experts: roles focused exclusively on the use and maintenance of tools to support DE/MBSE. Workforce development is a critical component of DE/MBSE adoption, and this research provides an initial survey-based framework for DE roles and skills. The results of the MBSE Maturity Survey conducted with this effort capture this framework[10].

11) If one were developing a "Program Office Guide to DE/MBSE Transition," a desired outcome of this research process, one would start with a high-level description of program adoption practices linked to the benefits of DE/MBSE, then use these to design a set of organizational capabilities for doing DE/MBSE, measure the performance of the organization within each of these capabilities, and use this to produce results that enable new value to the organization. This starts with leadership and strategy; is implemented across enterprise operations and workforce capabilities; and should produce customer value and enterprise-wide results. This is the core of the Baldrige Criteria for Performance Excellence. Although this research was not able to produce a "cookbook" for program office success, it does provide a set of frameworks for a program office or enterprise to evolve that guide.

11) Finally, there appears to be a strong top-to-bottom leadership commitment to DE transformation at this point in time, but the perception of progress and success differs greatly between leadership and the workforce using the methods, processes, and tools. In terms of the Gartner Hype Cycle[11], the community is just starting up the "Slope of Enlightenment" where benefits start to crystalize and become widely understood. A strong understanding of adoption obstacles and enablers must exist and be tracked at all enterprise levels.

[10] McDermott T, Van Aken E, Hutchison N, Salado A, Henderson K, and Clifford M. (2020), Technical Report SERC-2020-SR-001, Benchmarking the Benefits and Current Maturity of Model-Based Systems Engineering Across the Enterprise: Results of the MBSE Maturity Survey, March 19, 2020.
[11] https://www.gartner.com/en/research/methodologies/gartner-hype-cycle

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