Abstract
Model-centric engineering (MCE) is an overarching digital and visual approach to engineering. It also involves integrating diverse model types, surrogates, systems and components at varying levels of abstraction and fidelity across disciplines throughout the system or solution lifecycle. The use of such digital engineering technologies and model-centric engineering practices are advancing, and its adoption is accelerating. Concurrently, a number of technical and business/acquisition challenges remain. As an example, the existing business models may not be optimally aligned for acquisition in a model-centric ecosystem.

Digital technologies are changing how organizations are conceptualizing, architecting, designing, developing, producing, and sustaining systems. Some use model-centric environments for customer engagements, including design engineering analyses and review sessions. Others are integrating mission and system-level modeling and simulations originally created for design and development and expanding them into new cloud-like services enabled by the industrial Internet. Most organizations today have developed unique capabilities derived by integrating commercial technologies and tools with their own innovations.

The Systems Engineering Research Center (SERC) organized an Industry-Government Forum to gain insights from key stakeholders in the user community on how to transform our engineering and acquisition culture in light of these advancements, and how to align engineering and business/acquisition models. The forum also explored ideas and concepts to improve efficiencies in speeding the development, deployment and sustainment of needed capabilities to the warfighter.

The intent of this Forum was for key stakeholders in industry, government, and academia to converge and identify high-value shortfalls that remain in model-centric engineering that can be addressed through focused research and policy. This paper highlights the primary insights and challenges identified during this forum.

1.0. Forum Context, Structure, and Audience
The Model-Centric Engineering Forum was organized to ensure a balanced perspective between industry, government, and academia. Fifteen faculty members from across the collaborating SERC universities participated, along with thirty-five technical leaders from industry and twenty-five technical leaders from the government. The structure of the forum was crafted to allow significant interchange and dialogue, with three contextual talks:

1. The Need for a Transformation – A Government Perspective, Mr. Dave Cohen, Director, Mission Engineering & Analysis Dept., NAVAIR
2. The Need for a Transformation - An Industry Perspective, Mr. Aaron Copeland, Director, Systems Engineering, Mission Systems Sector, Northrop Grumman
3. Current State of Research and Development in Support of Engineered Resilient Systems (ERS), Mr. David Richards, Technical Director, ERS, ERDC
Two panels:

Panel 1: How the Government & Industry Can Collaborate More Effectively
Moderated by: Mr. Robert A. Gold, Director, Engineering Enterprise, OUSD(AT&L)/ASD(R&E)/Systems Engineering
Panelists: Ms. Carla Coleman, Huntington Ingalls, Inc. - Newport News Shipbuilding (HII-NNS); Mr. Mr. Dave Cohen, NAVAIR; Mr. Don Kinard, Lockheed Martin; Mr. Paul J. Russo, US Navy; Mr. Mark Signorelli, BAE Combat Vehicles; Col. Kelly Tucker, US Air Force

Panel 2: Tools and Infrastructure in support of Model Centric Engineering - a Tool Vendor Perspective
Moderated by: Mr. David Long, CEO, Vitech and Former President, INCOSE
Panelists: Dr. Dave Richards, US Army ERDC; Mr. Barclay Brown, IBM; Mr. Venkat Parameshwaran, Altair; Dr. Scott Ragon, Phoenix Integration; Mr. Don Tolle, CIMdata, Inc.

My challenge to this audience is to envision a community that seamlessly exchanges information, performs analysis and evaluation, and makes decisions all using models. And these models are maintained and mature over time.

By a model, I mean data, algorithms or processes, or a hybrid of all three. When coupled with the computing power and software techniques of today, we can realize our concepts, capabilities, and evaluations in new ways. My challenge envisions that a seamless exchange across the govt industry internal and external boundaries, across multiple stakeholders, strengthening our technical communication and providing the best value to our warfighters. This is one focus for today’s workshop - determine the methods, processes, and tools to enable this outcome. Are these areas of research? Or are there existing practices that we can proliferate?

In order to realize this vision, we must also assess the benefits. Can we not only strengthen communication across multiple technical, evaluation and programmatic communities, but also:

- Avoid cost of rework or requirements change
- Reduce risk due to interpretation of language
- Accurately planned maintenance, and more efficient sustainment operations

Ms. Kristen Baldwin, Acting DASD (SE)

And two breakout sessions:

Breakout 1: Discussion on a Collaboration Operational Model between Industry and Government
Moderated by: Dr. Donna Rhodes, Director, Systems Engineering Advancement Research Initiative (SEArri), MIT; Principal Investigator, SERC

Breakout 2: Discussion on Capabilities of New Operational Paradigm
Moderated by: Dr. Jon Wade, Director, Systems and Software Division and Distinguished Research Professor, School of Systems and Enterprises, Stevens; Chief Technology Officer, SERC

The overall forum direction was provided by Ms. Kristen Baldwin, Acting DASD (Systems Engineering).

2.0. Summary of the Contextual Talks

2.a. The Need for a Transformation – A Government Perspective (Mr. Dave Cohen, Director, Mission Engineering & Analysis Dept., NAVAIR)

Model Centric Engineering is central to our ability to maintain a tactical advantage, and there is a need for a shared vision of an end-state with a cohesive, integrated plan to achieve it. This must leverage the engagement of the broad community to instill model centricity into current practices where practical. In the face of rapidly changing threats, there is a compelling need for acquisition organizations to instigate improved methods for greater speed in developing systems. The historical
technological advantage of the United States is quickly eroding as technology advances enable rapid advancements for organizations and countries that may pose a threat. There needs to be a change in focus. Rather than thinking about individual systems (Programs of Record (POR)), new thinking must be expanded to the Integrated Warfighter Capability (IWC) where the broader interests involve selecting capabilities to systems that add value at the mission and campaign levels.

Large numbers of detailed requirements at the system level add complications, leading to higher program costs and risks, and a reduced feasible design space too early. Focusing on a small number of key (sacred) requirements, then developing the concepts, designs, and architectures to enable detailed requirements flow out is ideal. Greater application of methods such as set-based design is necessary. In some cases, requirements should be used to document reality at the end, versus driving the design in the beginning. Currently, certain programs use the V-model causing possible disparate parallel universes where one team is focused on audits, checklists, and compliance; while the other focused on reality. We need to rethink systems engineering to move from a Newtonian paradigm to a Quantum paradigm. With recent advances and demands, a natural evolution of systems engineering outside the classic model is needed; we need to affect a move from the existing (document centric; fixed phase driven) inefficient and restrictive acquisition to one that achieves fast, iterative and test-driven development.

Quickly built flight test vehicles used to be common, but since acquisition reform, early builds of test vehicles is rare. Therefore, changeable and adaptable end products are not being built. The Department of Defense Architecture Framework (DoDAF) architectures were not carefully thought through. Architectures of the future need to be developed so that there is a flow down of open, honest information into intelligent architectures and design – making them live and dynamic, with integration at the top level. The holes while working at the mission level need to be filled, and MCE can provide the appropriate solution. This practice would focus testing and refining concepts through war-gaming, modeling, and simulations.

Movement to third offset strategies while recognizing that there are no silver-bullets will require war-gaming and operational concept development supported by discussions with allies and commercial partners to try and figure out the path forward. The third offset is a combination of both new capabilities and new concepts of operation, with investments falling into six targeted areas: anti-access and area-denial, guided munitions, undersea warfare, cyber and electronic warfare, human-machine teaming, and war-gaming and development of new operating concepts. A system’s Initial Operation Capability (IOC) should be achieved as soon as possible and, to achieve that, the government needs to work with contractors differently.

About 3 years ago, with our interagency partners, we established a working group to address complex systems engineering challenges. Our peers in NASA, DOE, VA, NSF, DHS, FAA, NIST, NOAA all share common challenges. We recently formed a subgroup to address today’s topic with our interagency partners, and learned that the benefits from a model based approach may be different, depending upon the type of activity, perspective, from the different agencies. That said, there was common ground. Leaders from across the Government express expectations that MBSE infusion into their organizations will provide:

- Informed decision making through increased transparency and greater insight
- Enhanced communication with less interpretation
- Understood flexibility and adaptability of the end item
- Increased confidence that the end item will perform as expected
- Increased efficiency in methods and processes

We know MBSE is happening; what we need to do now is change our cultural, historical, business processes. In order to do this we need to highlight crisp examples of how programs have benefitted, what the technical practices can achieve, what organizations have seen an ROI. This is my third focus area for today’s audience. Can we identify examples, use cases that can be used to highlight how a model based approach can achieve the same outcomes, but with additional efficiency, knowledge, and other benefits that we hope to achieve.

- We should seek to learn from what Industry is doing both from their practices, and their experiences, to the largest extent practicable
- We should also seek to learn from what is already working in Government, and how we can proliferate these practices.

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The government should enable the contractor to integrate new and evolving capability into mission-level simulations. The Intellectual Property (IP) should not be taken away from contractor, but optimized to have greater assurance that contractor Program of Record systems can quickly address technology gaps needed to tackle evolving kill chains. By knowing the physical aspects of the systems to meet the needs, the contractor will be able to start efforts for getting all necessary materials earlier. For these efforts to be successful, there also needs to be an Integrated Engineering Environment.

Working with industry in using a new concept of “role-based” approach with capability views and functional views through MCE can aid in finding additional issues and anomalies within the system. These views need to be dynamic and carried to the platform with better traceability. Also, the diversity of domains and disciplines involved need to exchange information in order to make sound decisions with the models over time and as the capabilities evolve. Currently there are few accepted “correct” sets of methods, processes, or tools, but they need to enable seamless exchange of information that is vendor and tool-agnostic. Decisions need to be more informed and have increased transparency with greater graphical, dynamic, and gaming aspects through the Capability Development Document (CDD). Also, there is a necessity to have the CDD trace into the operational and system views to enable them to be rightly sized.

2.b. The Need for a Transformation – An Industry Perspective (Mr. Aaron Copland, Director, Systems Engineering, Mission Systems Sector, NORTHROP GRUMMAN)

There were several model-centric efforts at Northrop Grumman that ultimately led to MCE being implemented in all areas. The company as a whole is committed to making the transformation to MCE, and they have seen better response to demand of market and environment. There has also been greater ability to deal with the complexities of systems where the performance for the customer was enhanced due to MCE.

However, there are still issues and challenges that industry faces such as:

- Lack of standard operational architectures
- Lack of common standards
- Need for a smaller set of standards
- Right model with necessary abstraction levels plus appropriate fidelity in selected domains

The engineers have learned that model fidelity when developing payloads is the key to the actual physical system, and some great stories are that “high fidelity” today can be achieved by the actual software that is integrated into the simulations.

2.c. Current state of research and developing in support of Engineered Resilient Systems (ERS) (Mr. David Richards, Technical Director, ERS, ERDC)

The Department of Defense (DoD) goal for Engineered Resilient Systems (ERS) is for Resilient Materiel Systems. A resilient system is reliable and effective in a wide range of contexts, easily adapted to others through reconfiguration or replacement, and has predictable degradation of function. The ERS framework allows for specific tailoring with the use of integration of visualizations, utilizing advanced computational power to “buy down” risk. The work leverages the High Performance Computer Modernization Program using capabilities such as the multi-physics Computational Research Engineering Acquisition Tools Environment (CREATE for ground, rotor-wing, fixed-wing and ships) to perform tradespace analysis to assess millions of designs. It has become the government development of a trade studio with computational notebooks that can be developed into families. The framework also tailors to service workflows with methods to define the tradespace, and a computational notebook developed with a wiki-like interface. The tailoring enables the tools to
restructure to organization tooling around the data, as it is too difficult to move “big data.” The future plans include integrating gaming technology to explore operational concepts.

3.0. Summary of the Executive Panel: How Government and Industry can collaborate more Effectively

The emergence of enabling MCE capabilities makes it important that a government component or a contractor playing the role of a Lead System Integrator be better able to leverage MCE data to allow effective mission and system analysis for rapid deployment of system of systems capabilities. Further, the complexities of modern evolving systems means we must be able to perform syntheses and analyses, and share digital artifacts and information across diverse domains and disciplines, as well as diverse systems. The intent is not for the acquisition organizations to impose digital engineering technologies on contractors and but rather evolve to it in a collaborative manner while maintaining healthy competition. Challenges include, but are not exclusive to, appropriately acquiring and using government data rights, intellectual property marking and protection, and contracting using digital engineering artifacts and evidence as deliverables. Another challenge is the MCE framework for collaboration spanning the lifecycle – addressing the security for different levels of classification and aggregation, the appropriate levels of visibility and transparency, and making use of increased technical cohesion.

The integration of systems of systems is so complex, the classic V-model does not allow for the quantum systems engineering needed. Asynchronous movement towards a better preliminary design and what information is needed to start development is necessary. Operating in a parallel-type universe with knowledge on what is actually going on allows time to effectively make decisions with minimal hindrances. All parties are currently operating too much in the audit mindset, creating enormous amounts of requirements and resulting in long lead times before a systems or solution even goes to test. The modeling environment can drive down the number of requirements while facilitating the product to be in test rapidly, allowing for test driven development. As an example, there is not a pressing need to address everything about the software-enabled functionality of the system, but rather, put focus initially on only the functions needed that contribute to the physical system’s core capabilities that provide focused value to the mission.

We need to rethink the concept of the V-Model. The same goes for the current and accepted concept of a linear phased approach to acquisition. Focusing early through a small set of key or sacred requirements to embed the notion of validation, and test driven development can allow us to capture the potential of model centric engineering. The ability to capture knowledge in models (reference architectures, design and architecture patterns, design and architecture rules) within the context of accepted ontology can bring increased efficiency. What information is needed should be determined early to allow early and better cost estimates. Aspects of the digital thread and digital twin should harness and capture knowledge to ensure that it does not have to be reinvented every time and is representative of what is being sought by customer or use. As the digital thread feeds manufacturing, if a digital twin were present, it would provide the basis of operations and sustainment, and evolution. The digital twin, which is related to the Single Source of Technical Truth (aka Single Source of Truth, a single authoritative representation of the system, Digital System Model), would contain appropriate data rights going into a more dynamic/living system model with operational data for both operations and sustainment. MCE should be ubiquitous, but non-intrusive, giving the ability for selected key stakeholders to be inside various decision loops with contractors.

While the number of requirements in a complex development program often exceeds human comprehension, the interchange between industry and government on the comprehension of the requirements can be improved through MCE. Both parties should be using MCE for designs and communications since it is infinitely better than a document containing numerous pages. All documents exist in a model somewhere. The idea of composing and visualizing requirements through a simulated environment may take a paradigm shift. As an example, the current decision making process focuses on what it costs today versus what it will save tomorrow. The complexity of today’s
systems means we must be able to perform and share “digital” artifacts and analyses across many domains and disciplines as well as across system of systems.

The ability to reuse models will become important if they are trusted in another context – as a continuous representation of the system across the acquisition lifecycle. The representation of the mission could be more accurately accepted through understanding of how functions used add value in operational space and placing greater emphasis on systems thinking within that space. A deeper understanding of the total lifecycle system cost needs to be performed. Increased analysis of MCE for manufacturability helps provoke thoughts of sustainment and operations even down to the component level. The appropriate views and viewpoints are necessary for the model since increasing complexity tend to inherently make the models larger. Leveraging the willingness of the new generation of engineers’ ability to use new technologies for MCE can break the current culture of hesitancy.

MCE will improve both the ability for developers to address manufacturing needs during development, and readily transition the results of their efforts to manufacturing once that development is mature. There is more modeling and simulation into manufacturability as an extension to the tradespace analyses. Two of the most critical areas where MCE could improve manufacturing outcomes are: performing tolerance stack-up assessments, and improving the ergonomics of complex manufacturing or assembly operations. There are new technologies being used on the F-35 that were not available when the F-22 was developed. There are new techniques for tolerance management for composed systems, human-systems ergonomics, assembly using projection devices, virtual reality, structure light – comparing “as designed” with “as built,” support for first article validation, and leveraging many capability already in play in automotive industry.

An example of integrating MCE throughout the product lifecycle is with NAVSEA and Huntington Ingalls Newport News Shipbuilding. The two are working together to develop the Product Data Model (PDM). The IP and data rights issue were addressed by agreeing that government owns what to build and how it is designed while the contractor owns how it is built. To address security concerns with the PDM, different views were created – view to customer (indirect), open full view (direct view into PDM), indirect exchange, and direct exchange (for data updates). The program called for government and contractor to work side-by-side, with approximately 100 requirement changes due to how “it can be built,” deciphering between actual requirements and desires. The stakeholder involvement to obtain buy in on how to accomplish change in operation was necessary, and there is anticipated need to continually change. For instance, the future CVN80 plans include having everything digital, where the stakeholder can constantly see the evolving digital model and the actual construction in the shipyard will be performed using portable computers and virtual reality headsets.

4.0. Summary of the Two Breakout Sessions

4.a. Breakout Session 1: Collaboration Operational Model between Industry and Government

Model-based engineering is a recognized practice, with established procedures used throughout the systems community. The differences in model-based practice and broader model-centric engineering need to be defined as a basis for establishing a collaborative operational model between industry and government. A collaborative operational model is needed to align the communications and the design and integration activities under the model-centric paradigm. Tools on their own do not provide transformative capability through their use; a key element of transformation is a focus on mental models that enable common thinking and discussions of what it means to collaborate in a model-centric environment. Further, digitizing legacy specifications and models should not be confused with a digital systems model approach to system and system of systems.

Orthogonal perspectives need to be addressed in converging on a collaborative operational model for model-centric engineering. Government should focus on the dimension of capability (available and gaps). Industry should consider requirements, mission-based, and operational aspects. Tool developers need to focus on providing toolsets to enable the ability to explore, synthesize, and make
decisions. Each of these dimensions impacts the other two. This was notable through many references to the adoption of an evolving and dynamic operational model.

The early engagement, especially during acquisition downtime, can help cultivate a MCE process and corresponding mental model throughout the lifecycle. Data sharing and general sharing in an open space would cause support for extended and extensible models to promote consistent attention to the design. In order for this to occur, there needs to be trust within and across each culture. Shared perspectives on operational use need to be present, and sustained to support to dynamic needs that arise during the use of model-centric approaches throughout the lifecycle. An environment for enabling individuals to understand models and their uses within a model-centric engineering context is necessary for convergence of mental models.

The group broke out into four smaller groups to discuss capabilities, opportunities (enablers), barriers, and breakthroughs for an effective collaboration operational model between industry and government. These are captured below:

**Capabilities:**
- Policy, processes and technologies enable joint, shared collaborative environment
- Culture (particularly with new hires) embraces model-centric engineering across the lifecycle
- Shared common understanding of model-based deliverables allows all stakeholders to make decisions
- Open system/framework supports tool agnostic use for users (design, manufacturers, sustainment, decision makers, operations, etc.)
- Standard interfaces facilitates and allows for sharing data across the stakeholder community
- Environment enables right data to be available for the right folks, with proper context, for decision-making.
- Data is more open vertically, with appropriate access control
- Environment/culture where every day is a “design review” for the entire IPT (government, contractor, decision makers), throughout the lifecycle
- Workforce possesses right skills, mindset, and organization to use visualizations, models, and data for rapid decision making (non-audit mentality)
- Early engagement of the logistics, supportability, and sustainment community, with lifecycle cost approach
- Early tradespace analysis and standardization of methods
- Open design space, using value-based (vs requirements-based) approach
- Models are “kept alive” through adequate funding and appropriate resources
- Environment enables right data to be available for the right folks, with proper context, for decision-making.
- Effective knowledge management of model/model information with access to stakeholders

**Opportunities:**
- Education, training and policy are all key to changing the culture
- Establish government endorsed processes and tools
- Establish tool standards and open architectures
- Enable open data through top decision-maker/leader endorsement and commitment, and multi-level access control
- Leadership commitment to lifecycle cost approach
- Endorsement and funding for knowledge management for model-centric engineering
- Use culture to foster collaborative approach for decision-making (i.e., agile methods beyond Statement of Work)
- Ensure clear understanding of what decisions are needed, with data analytics to provide what is needed to each stakeholder
- Develop IT solutions for joint shared collaborative environment
- Well-defined CONOPS and mission analysis connecting to user value
- Enable funding for modeling activities through saving with more rapid development
- Create an appetite for alternative deliverables

**Barriers:**
- Establishing joint, shared collaborative environment inhibited by culture, trust and funding
- A status quo culture, with skill gaps in workforce and current approach to acquisition deliverables on contract
- Culture, legal, security/access rights inhibit “every day is a design review” approach
- Incomplete set of standards and lack of understanding of model-centric engineering process and technologies
• Lack of standards, definitions, and terminology (lack of commonality between all as well – across disciplines and domains) are barrier to open framework
• Open data inhibited by technical/business IP, funding/color of money and short sighted programmatic decision-making
• Lack of funding for early engagement of downstream disciplines leads to lack of consideration of lifecycle cost approach
• Trade-space exploration paradigm not fully accepted, and different tool choices and methods for trade-space exploration are barrier to collaboration
• Unconnected or disconnected models, across domains and disciplines inhibit collaboration
• Insufficiently trained government and industry workforce
• Too much reliance on current data, approach, methods and tools
• Too much data, versus right amount of data presented in right way for stakeholder
• Current tools that are isolated and stove-piped
• Continuing the traditional way of thinking with overly defined contracts

Breakthroughs:
• Early adaptor/adopter successes and case studies
• Streamlined approach for industry and government to create new standards
• Develop means to foster the appetite for alternative deliverables
• Open up design space – value-based vs. requirements-based
  o Instead of continuing the old way of thinking with overly defined contracts upfront.
• An open system/framework that support tool agnostic use for users (design, manufacturers, sustainment, decision makers, operations, etc.)
  o Enforcement of standards
• Workforce with the right skills, mindset, and organization to use visualizations, models, and data for rapid decision making (non-audit mentality)
  o Education/training and policy
• An environment to enable the right data to be available for the right folks, with proper context, for decision-making.
  o Tools, training, acquisition strategy

4.b. Breakout Session 2: Discussion on Capabilities of New Operational Paradigm

Instead of relying on the systemic, linear progression through the V-model, a paradigm shift is necessary to allow development to flow with minimal impedance - this capability which is vital to program success MCE. We can take a cue from Silicon Valley by reducing program risk early and understanding the real costs necessary to support system development and integration. Appropriate models and their aggregation can enable a clearer perspective on uncertainty and systemic risk. Answering the question: “What models are needed and what value can they deliver for stakeholders and engineers?” will allow focus, so that failure is minimized. Narrowing the scope on what needs to be accomplished (product) to provide mission success, will allow a focus on the information necessary to drive decision making while recognizing there are fundamental implications at hand – there is no such thing as a silver bullet, and, at times, some aspects of verification and validation cannot be accomplished. Regardless, determining up front what data is needed and what can be captured at that moment can drive the collaboration to conceptualize a more complete model in the beginning with smoother iterations to follow.

The literature shows that the greatest value of model centric engineering may not necessarily be in reducing initial cost and labor, but rather in terms of reducing system defects and risks, and reducing long-term costs and increasing the system benefits. The post release incremental costs of systems are often driven upward when the focus is solely on reduction of acquisition cost, and this is where MCE can improve life cycle cost analyses. However, the ROI needs to be broad-based for MCE and needs to consider the overall system lifecycle, showing how breaking the barriers of the V-model with MCE increases efficiency, allowing earlier detection of defects and risks that otherwise may not be found till the later development stages. MCE should also allow consideration of long term sustainment
factors during the design decision making process. With early design reviews using MCE, there is the capability to shift from showing slides and talking qualitatively about the situation to providing concrete quantitative evidence to shape the decision making process. This enables stakeholders to address risk upfront, and obtain value on the front end. Doing more upfront model based investigations may increase the duration of the early program phases, but will likely provide a clearer view of the design space and associated risk, and help eliminate potential show-stoppers thus improving overall program quality and schedule. A conscious effort is necessary for a realistic assessment of the value that models can provide and how they should be used in the lifecycle process.

Knowledge transfer is key to the success of model centric engineering, along with the development of a model library. An immediate concern for legacy technologies and systems has to do with the ability to integrate existing models. If there is no MCE present within an organization, it can be an enormous barrier to introduce MCE. However, one example of success is the submarine warfare tactical system. The fleet was upgraded post-deployment by moving from document-drive to MCE. MCE was incredibly successful, and is now sought for by other programs. With being digital from day one, a minimal line model could be constructed without all of the features fully implemented. But as a minimum this allows a capture of the problem being addressed. High fidelity is not necessary everywhere - when building models into existing systems an assessment of the necessary details showing capabilities and interfaces where one can know how to utilize them in different situations or additions is crucial to success.

The idea of leveraging models for program and design review begs the question of model integrity. However, it is speculative whether or not the current approach to conducting design reviews using PowerPoint is any better. The discussion alluded to a need to integrate the customer into the model building process, allowing them to see the inputs, assess the value, and assess the appropriate level of abstraction. As an example, system design reviews could be implemented without the need for traditional contract design requirements lists (CDRL). The model itself becomes the all encompassing CDRL, where there is the ability to perform multiple deliveries of updated systems that are continuously available with incremental releases.

After general discussion, the group broke out into four smaller groups to discuss capabilities, opportunities, barriers, and breakthroughs necessary to support a successful paradigm shift. The results are described below:

**Capabilities:**
- With the model centric approach – there could be a single logical model throughout lifecycle, whether it is integrated or federated.
- Enable a standardized validation and verification process for the models being used
- Associating risk across the set of models with visualizing the appropriate fidelity and access
- Eliminate classical document centric reviews, replaced with evidence based models
- Better understanding of tradable values of requirements to the mission/customer
- Increasingly flexible designs to allow for showcasing better future adaptability
- Single system Source of Truth
- An architecturally driven model-centric environment
  - MCE could improve rigor in design, finding gaps early and often, better risk and expectation management.
  - Regardless, the model library buildup and the architecture will be built up over time, across generations of systems, allowing the MCE to get faster and cheaper.
- Ultimate vision is to have a fully integrated set of models, performing integrated analyses across domains and disciplines - both vertically and horizontally.

**Opportunities:**
- Identified tools and methods to build, manage, and use sets of models within an environment

**Barriers:**
- Cultural issues with a reliance on the document centric CDRL paradigm
- Lack of common interface standards
• Ability to list assumptions properly across all stakeholders
• Security of IP and skill base associated with the models
• Implementation approach of Cloud vs. high performance computing (HPC) creates barriers to forward movement within certain contexts
• Knowledge transfer and building context awareness and transferability, having the appropriate viewpoints to enable curation of knowledge needed to leverage reference and historical aspects of initial buildout
• Understanding the right fidelity at the right time – the value of what is being performed when
• If there is lack of context awareness, there could be a misuse of legacy
• Lack of centralized data ownership
• Fostering methods awareness and leveraging the appropriate technology through curated knowledge to provide a sufficient set of tools
• Lack of an integrated, consistent modeling approach
• Lack of adequate and sufficient models to support state of the art engineering
  o The ability to link models with varying levels of abstraction, which depends on an understanding of the linkages of complex phenomena and behavior across disciplines and domains, and abstraction levels.
• Proprietary models limiting sharing
• Ability of MCE to support innovative conceptualization I
• Lack of accepted methodology for applying MCE in engineering processes
• Limited number of success stories and case studies
• Need for a program management type of framework, without going to a one-size-fits-all approach

Breakthroughs:
• What is the role of advanced software methods – can they be leveraged in the approach to integrated modeling?
• Is it possible to construct a model translator?
• Can we provide full lifecycle visibility with visualization capabilities?
• How will tutorials of what has been done be made freely available so that new participants can ramp up quickly?

5.0. Summary of the Tool Vendor Perspective Panel: Tools and Infrastructure in Support of Model Centric Engineering

The tool vendor panel took the opportunity to discuss challenges and gaps in industry and government collaboration, while leveraging model centric engineering. One challenge is how the request for proposals (RFP) articulate the intent. This can involve an imposition of specific tools or allow the contractors flexibility with the integration of appropriate and newer tools or HPC/cloud computing to do tradespace exploration. The ability to build adaptive models and use them in a responsive manner would be excellent and a step forward to breaking barriers and encouraging communications across the lines immediately. This also enables contractors to innovate with regard to program and project management, risk management, and baseline management. Ways to enable innovation would be more appealing and enable greater exploration for the vendors, allowing team to assess whether and how MCE makes sense. If the model-centric specifications were focused on what and why, instead of imposing specific MCE tools, then the contractors and vendors have requisite flexibility to adopt and adapt the best tools.

While there are technical issues within MCE that must be addressed by both the vendor community and the contractor community, there are also notable non-technical challenges that must be overcome. The cultural issues of changing how engineers work, how engineers communicate with subject matter experts and stakeholders, and how information is passed across the contractual boundary are key inhibitors to the adoption of MCE. Likewise, as we connect the product lifecycle to make MCE a reality, information will need to span organizational boundaries and this will result in IP issues from the customer, contractor, and supply chain perspective.

Emergence of the MCE tools make it paramount that government as the Lead System Integrator be better able to leverage MCE tools for effective in mission and system analysis for rapid deployment. With today’s complexities, it is unlikely for any single tool suite to cover all facets of the multiple
disciplines needed, and there must be the ability to perform and share analyses across domains and disciplines. The right set of standards would well equip an environment for collaboration, cooperation, and yet healthy competition. However, there is still a lack of tool integration and a need to go beyond linked data, and no one company complies with all of the standards since tool vendors are forced into specific tool-to-tool integration. The current proliferation of standards has contributed to market confusion on the vendor and contractor side with insufficient alignment and adoption. The lack of interoperability shows that there needs to be more cross-domain systems engineering and thinking. Regardless, standards regarding interoperability are necessary, and though it may stray outside of MCE named standards, it will support what is needed to accomplish a successful and integrated model-centric program.

6.0. Discussions during the forum and the hot-wash following the forum
This section incorporates selected insights resulting from discussions between the participants

1. There seems to be a need for a well-defined “game plan” to guide leaders looking to transition their organizations towards greater model centricity. What are the pre-requisites? What is the best approach, given that the context of any organization is unique? How to assess the necessary skills? What are the generational issues – and how best to address these?
2. What is the technical makeup of the canonical design team in a model centric context?
3. There will be a need to move from implicit designs (for legacy systems, where we know the design, but not the design rationale) to explicit designs (where we know the design, and also the design rationale). We cannot change what we do not understand. We need to think about how to evolve this attachment to a transformed paradigm, while enhancing the effectiveness and efficiency of the engineering and program management functions.
4. To better understand and address cultural issues with MCE, there should be a pragmatic explanation of the why, what, and how – particularly in the face of evolving and increasing program and system complexity and mission adaptability, and a need for rapid response. There is a technical makeup of canonical design teams that should be understood.
5. The ability to show the ROI associated with investing in the development of an MCE capability seems to be key to adaptation. Would it also make sense to develop a model-centric visualization of the current acquisition system by taking a step back from the system and focus on the ecosystem?
6. With the mission engineering world, there needs to a roadmap of what MCE would bring to the table. What is the limit on the speed within the current paradigm and mindset versus what it could be? Also, with the biggest struggle being the change in business, there is overlap between MCE and a drive towards increased modularity where it makes sense. There is a DoD priority on modularity with basic definitions, but no rules and no uniformity with regard to measurement and assessment. With the above, there needs to be a balance between theory, transition, and execution.
7. The tool integration standards and a change in the DFARS to eliminate the need to ask permission for reuse are worth exploring.
8. There is a need to develop guidance on how to put MCE on a contract with sample language describing deliverables, government furnished information, evaluation criteria for saying that we are going to evaluate their proposal on how they plan to exchange model-centric info.
9. How do we get a mental model of the programmatic data (my data versus your data) that is representative of IP barrier that has to be collectively overcome? Model centric engineering seems to have evolved to cover a collection of ideas with a diversity of mental models, linked with the notion of computational models. More specificity is necessary, while allowing flexibility in implementation.

During the course of the day, recurrent themes clustered into four perceived areas of benefit:

A. Improved Acquisition
• Accepting digital models as deliverables during the acquisition process (as opposed to digitized documents) could improve the government’s understanding of a project’s status and risks as well
as reduce the workload associated with generating and reviewing documents for both government and contractors. The government could use their own analysis tools to computationally validate a contractor’s deliverables in a way that is not possible with documents.

**B. Improved Efficiency and Effectiveness**

- A digital “twin” of the system under consideration can be used to expedite production activities and maintenance activities as well as perform “what-if” analyses and test the effects of operational changes. All of these could result in reduced time and effort in the performance of existing tasks.

**C. Improved Communication; Better Trade-Space Exploration; Reduced Risk**

- While digital models are already used extensively in system development, each stage of the development as well as each specialty/domain has its own suite of modeling and analysis tools and these are often incompatible. (e.g., it might not be easy to extract useful information from a hardware model and import it into a cost model) As a result, translation among the various tools is time consuming and error prone. Greater model transformation across domains and disciplines could potentially improve communication among specialists as well reduce work and errors.

**D. Improved Designs and Resulting Systems and Solutions**

- Today it is often difficult to understand the impact of a requirement or a design decision until late in the development process when test articles are built or detailed, system specific simulations are completed and validated. Consequently, adverse consequences from an early requirement or design decision may not be recognized until late in the development process when the costs and time to correct are substantial. Multi-scale simulation using “off the shelf” or modified models could be used to perform detailed and extensive trade studies to identify these adverse consequences before a commitment is made to requirements and/or design decisions.

**7.0. Industry-Government Forum Participants**

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