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Future Model-Based Systems Engineering Vision and Strategy Bridge for NASA

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Future Model-Based Systems Engineering Vision and Strategy Bridge for NASA

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Summary

A vision for the future of model-based systems engineering (MBSE) at NASA in 2029 and a strategy bridge towards that future are presented. Strategic thinking and leading change concepts were used to analyze reports and presentations on global trends and visionary thinking about the future of systems and digital engineering. The context, strategic time horizon, stakeholders, strategic challenges, strategic advantages, driving forces, and opportunities were considered. The analysis resulted in a future vision of MBSE that shows what NASA systems engineers and digital machines will do to perform rapid, extraordinary, and unprecedented missions. The NASA systems engineer, in this future vision, works with a global project team in a virtual and collaborative environment, engineers the system, and uses digital approaches as the routine and default way of working. The digital machines provide data-driven and automated mission designs; have a backbone of program and project management, systems engineering, and product life-cycle management; and are a knowledge-sharing infrastructure. The NASA systems engineer and the systems engineering team are envisioned to use digital machines to plan and perform rapid exploration missions, develop a digital twin that lasts across the life cycle, and develop enduring and adaptable systems. NASA has an engineering enterprise and a life-cycle management framework that endure, adapt, and respond. A strategy bridge based on the Baldrige Criteria for Performance Excellence Framework and lessons learned from a recent MBSE initiative illuminates a way forward from today to this desired future. The bridge lays out a strategy for leaders and recommends investments of today for immediate benefits and for benefits in 2029.

1.0 Introduction

Model-based systems engineering (MBSE) is 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 (Ref. 1). In late 2015, the first MBSE Pathfinder strategy and use cases were defined and the MBSE Pathfinder ran throughout 2016 (Ref. 2). The goal was to find out how well NASA systems engineers could use MBSE, and what the engineers knew and what they did not know about implementation and use on real projects. Over 30 participants from 8 of the 10 NASA centers worked on four teams, each with its own mission focus area. Most of the participants were less than full time on the MBSE Pathfinder. The teams were multicenter and everyone met as a large group for training and two face-to-face meetings but otherwise worked virtually. At the end of 2016, a review and knowledge capture meeting provided a treasure trove of findings, lessons learned, and recommendations for next steps directly from the participants. The following year, in 2017, the MBSE Pathfinder was expanded to more teams and involved additional partners and participants. The goal for this year was to find out why NASA should do MBSE and how to use it on projects to perform useful work. A technical peer review panel and a pilot of the MBSE community of practice (CoP) were added. Over 50 participants, with about 50 percent turnover between

2016 and 2017, were on the MBSE Pathfinder in 2017. These 2 years provided the information and confidence to proceed with further infusion into projects and building foundations for the user community.

In 2018, the effort was renamed to the MBSE Infusion and Modernization Initiative (MIAMI) to indicate the growth of MBSE use on projects and the establishment of an advisory board, expansion of the CoP, and a strategy group. Throughout MIAMI's 5 years, the participants worked virtually across centers and with partners inside and outside of NASA. Participants would often be part of MIAMI for 1 or 2 years, and carry their knowledge and expertise between MIAMI, their centers, and their project work. The virtual experience foreshadowed and made it easier for the MBSE user community to adapt to mandatory telework during the COVID–19 pandemic.

Figure 1 summarizes the timeline for MIAMI from its start in the MBSE Pathfinder through its completion at the end of September 2020. The downward trending arcs show the work in 2016, 2017, 2018 to 2020, and major events. The initial major themes are "Can We?" followed by "Why?" The upward arc shows progress towards more formal Agency adoption and direction from the Agency Program Management Council in the themes of "Infusion" and "Direction." The rectangles show the time period of the strategy group and future MBSE work.

The strategy group was established in June 2018 and ran for a year. It had 11 early to midcareer individuals from six different NASA centers who would directly see the benefits from their thought processes. The group collectively had knowledge of trends in political, technological, educational, organizational, and engineering areas; discipline expertise in areas related to systems engineering; and adeptness in one or more new technologies (e.g., augmented reality, virtual reality, gaming, MBSE, Internet of Things, data analytics, machine learning, natural language processing, etc.). The individuals were willing to experiment with unproven ideas; able to work across geographic locations; able to communicate and discuss ideas; self-starters; and interested in culture change, innovation, and creativity.

The strategy group was asked to consider a big-picture view of systems engineering at NASA, which would be digitally based and 20 years into the future. They produced a vision, a top-level roadmap, and a strategic approach that was technology focused (Ref. 4). A complete report of the strategy group is available in References 4 and 5.

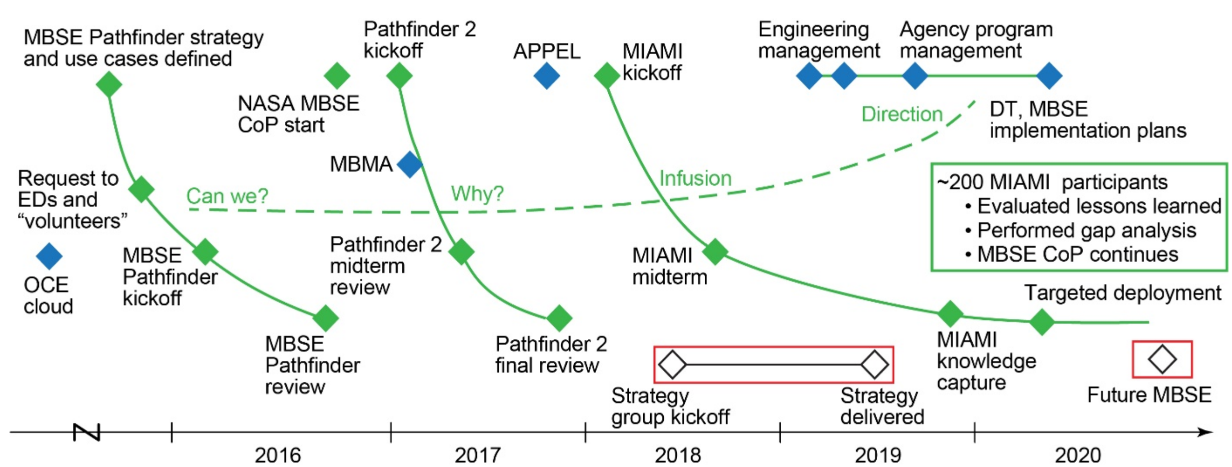

Figure 1.—Model-based systems engineering (MBSE) Infusion and Modernization Initiative (MIAMI) systems engineering digital strategy. Academy of Program/Project and Engineering Leadership (APPEL). Community of practice (CoP). Digital transformation (DT). Engineering directors (EDs). Model-Based Mission Assurance (MBMA). Office of Chief Engineer (OCE) (Ref. 3).

The follow-on to the strategy group work is the future MBSE vision and strategy bridge as described in this report. This vision and strategy bridge was one of the last major deliverables from MIAMI to the Systems Engineering Technical Discipline Team.

Although MIAMI ended in September 2020, the MBSE CoP continues with its 200+ members, a NASA Engineering Network (NEN) website, and a Microsoft® Teams™ channel. Over its 5 years, MIAMI garnered over 200 participants who now make up a "smart buyer" MBSE user community. The NEN site contains publications, reports, and modeling resources for the user community.

The MIAMI leaders have many lessons learned from the past 5 years, as do the participants themselves. The MIAMI leaders used the knowledge gained and lessons learned to evaluate gaps, point the way, provide recommendations for Agency leaders and broaden awareness for the NASA community (Refs. 3 and 6).

2.0 Approach

The approach had four major steps: identify and gather sources of information, extract insights and observations from the sources, analyze and generate conclusions and recommendations, and present the results through technical reports and presentations.

Papers, news articles, and reports of relevance to the future of MBSE were identified and gathered from NASA, industry, other Government agencies, academia, professional societies, and software vendors. Additional sources were the work done by the strategy group and a dialogue with the NASA MBSE CoP. The 17 sources used are listed in the Appendix. Observations of trends and environments, examples of visionary thinking about the future of systems engineering, digital engineering, and engineering in general were extracted from each source. The complete list of extracted observations is in the Appendix.

The analysis of observations relied on strategic thinking and change leadership concepts and tools. This included an examination of the context and selection of the strategic time horizon as well as consideration of stakeholders, strategic challenges and advantages, driving forces, and current status. The results were captured in the form of a vision, a gap analysis, and recommendations. The vision was depicted in both text and graphics with details of how future work processes, environment, and culture will differ from those of today. The gap analysis is presented in terms of what systems engineers will do in the future, what they will not do in the future that they do today, and why should anyone care. The recommendations for bridging the gap between the future and today were organized using criteria from the Baldrige Performance Excellence Framework (Ref. 7).

3.0 Observations and Analysis

This section discusses the observations and analysis results for context, stakeholders, strategic challenges, strategic advantages, driving forces, and the strategic time horizon.

3.1 Context

It is important to know the context of the world around NASA, both within and outside of aerospace, as related to MBSE. Social, political, technological, economic, and other environments affect NASA overall and how NASA does systems engineering. At NASA, the systems engineer plays a key role in the project organization (Ref. 8). Trends and changes in the contextual environment will affect the ways in which NASA does systems engineering for successful aeronautics and spaceflight endeavors going forward.

Two quotes illustrate the context of the global environment for aerospace organizations. The first quote is from Eric Pearson, the Chief Information Officer of the International Hotel Group, who said "It's no longer the big beating the small, but the fast beating the slow" (Ref. 9). The second quote is from Timothy West and Mark Blackburn, who wrote, "The digital transformation of the aerospace industry is well underway, and there is no turning back" (Ref. 10). The message from these quotes is clear: those who do effective digital transformation the fastest are more likely to be successful!

In its Digital Engineering Strategy, the U.S. Department of Defense (DOD) recognized the imperative for digital engineering and MBSE (Ref. 11). The DOD has the challenges of "balancing design, delivery, and sustainment of complex systems with rapidly changing operational and threat environments, tight budgets, and aggressive schedules." They are implementing digital engineering to improve responsiveness to threats and increase affordability, among other cited benefits. NASA has similar challenges for quicker timelines from idea to mission operations and to provide the best possible return on investment from taxpayer dollars for cost and mission effectiveness. NASA's investigation of MBSE during the MIAMI identified similar benefits in the areas of efficiency, effectiveness, priorities, and understanding risks and opportunities (Ref. 5).

To obtain a sense of the extent to which MBSE is being used or considered in the United States and which companies are hiring in this area, a search of job postings on LinkedIn in late September 2020 was done. The search criteria were MBSE jobs in the United States posted over the previous month. The search returned over 1,000 results. Aerospace industry companies and others in transportation and electronics, such as Ball Aerospace (part of the Ball Corporation), Bell Flight (part of Bell Textron, Inc.), John Deere (Deere & Company), and Honeywell International, Inc., were among those represented. These metrics provide a snapshot of how United States industry in many technical areas embrace the use of MBSE and seek staff with expertise in MBSE and indicate the competition that Government agencies such as NASA face for talent.

A digital transformation initiative is underway at NASA (Ref. 12). NASA senior managers see digital transformation as imperative to manage the risk of ambitious missions. MBSE is part of one of the six digital thrusts in the digital transformation initiative, that of model-based everything. NASA leaders acknowledged the importance of committed leadership to drive the effort and established a Digital Transformation Officer position in October 2020. Their strategy is to coordinate an enterprise-wide digital transformation. The work performed by the MIAMI leaders and participants was cited as an example of the importance of having the benefiting organizations assume ownership of the transformational change (Ref. 12).

3.2 Stakeholder Analysis

The observations that were analyzed for aspects related to stakeholders are listed in the Appendix. A summary of the stakeholders, expectations, and priority are in Table 1. The high priority stakeholders are systems engineers and their managers and program and project managers due to their direct interactions with the MBSE tools, the workforce, and the products from the tools. Software developers are also a high priority as they are needed to code, adapt, modify, and maintain the MBSE tools and the digital infrastructure in which the tools reside. The last set of high-priority stakeholders are the committed Agency leaders for digital transformation initiatives such as MBSE. Although other groups of stakeholders are listed as medium and low priority, all the listed stakeholders are important for the future of MBSE.

TABLE 1.—STAKEHOLDER ANALYSIS MATRIX

Priority[a]	Stakeholder	Expectations	Challenge for model-based systems engineering (MBSE) leaders
H	Systems engineers (SEs)	MBSE is how SEs do their work and is the backbone for all their work. SEs interact with other engineers, engineering managers, program managers, project managers, human resource specialists, and acquisition specialists in a digital environment.	Continue the momentum from MBSE Infusion and Modernization Initiative (MIAMI); Build the use of MBSE across the project life cycle
H	Systems engineering managers	Managers are trained and educated in MBSE to increase their knowledge and understanding of what it is and its value, in order to clearly guide and control an effective implementation.	Having systems engineering managers enthusiastically get behind and advocate for the changes implied by MBSE
H	Program and project managers	SEs get their work done and provide the information and products in a format that they can use to better understand the programs and projects they manage. SEs provide information for data-driven decisions. Much of the routine work is automated.	Getting program and project managers buy in to the new paradigm of MBSE
H	Software developers	A high demand to support the digital transformation exists. NASA uses ways to reduce the effort for software development and increase the pool of software developers.	Dedicated workforce with software competencies beyond the normal day-to-day work
H	Agency leaders	NASA has strong and corporate commitment to MBSE. Leadership expectations are clear and made known. Leaders delegate authority and resources to lower levels of management.	Systems engineering leaders pay sufficient attention to the development of the digital user community and look beyond the technology
M	Industry	NASA uses MBSE to collaborate with industry to deliver products and services with increased efficiency. NASA acknowledges that MBSE gives companies a competitive advantage. NASA has a corporate-wide strategy for MBSE that considers industry as a key partner in the approach.	Defining the interfaces (contractual and information technology (IT)) between NASA and industry for data and model delivery and exchange
M	Software vendors	NASA continues to purchase MBSE tools and IT. Large purchasers from other Government agencies and industry and the Object Management Group (OMG) drive the capabilities of the tools.	Leaders with sufficient knowledge of MBSE to make appropriate choices for where to allocate resources and investments; tool choice drives systems engineering processes
M	Engineers	SEs better enable engineers in other disciplines to get their work done in a more informed, efficient, and effective manner. SEs aid the discipline engineers and provide the information and products in a format that they can use as well as provide information for data-driven decisions. Much of the routine work is automated.	Integration of the data, information, and models across multiple disciplines
L	Academic institutions	NASA needs SEs who have coursework and experience in MBSE. NASA buys courses to train and upskill its systems engineering workforce.	Transition from academic training to actual use on a project
L	Nontechnical audiences	Visualization and experiential viewpoints allow nonexpert stakeholders to understand the models and provide timely and meaningful feedback.	Methodological aspects of tool language become noise because they are far outside their domains
L	Acquisition specialists	Acquisition regulations allow the use of models for acquisition activities (proposals, deliverables, etc.). A digital acquisition process has the steps to do this.	Acquisition specialists buy in to new paradigm of MBSE

[a]Priorities are high (H), medium (M), or low (L).

3.3 Strategic Challenges

The observations that were analyzed for strategic challenges for NASA are listed in the Appendix. Five major challenges emerged from the observations.

1. There is difficulty attracting and retaining workforce.
   a. Early-career, midcareer, and experienced people are leaving NASA for industry.
   b. Salaries, for civil service employees, are comparatively low for some locations.
   c. Rigid processes and overwhelming workloads are barriers to innovation.
2. NASA has large numbers of acquisitions from the aerospace industry in which companies are moving rapidly into digital transformation.
   a. NASA acquisition life cycles and processes may not align with an industry that is going model based.
   b. NASA interacts with industry through public-private partnerships and fixed price contracts to a greater extent than in the past.
   c. The rights and access to intellectual and data property and digital artifacts and NASA procurement regulations and practices may present legal and organizational barriers.
3. Availability of leaders and decision-makers who are familiar with understanding, leading and implementing MBSE, innovation, and change is insufficient.
   a. Many managers are familiar with technical advancements and less so with leading and implementing far-reaching innovation and change.
   b. There is a need for more committed leaders with authority and resources who provide clear strategic expectations that are aligned with innovation.
   c. Leaders and managers face difficulties in balancing their efforts to reduce barriers and remove roadblocks for innovation while minimizing disruption of critical and essential missions and services.
   d. Managers encounter obstacles when advocating for MBSE within current organizational structures and processes that expect document-centric systems engineering.
4. Development times for major efforts are growing longer.
   a. Government Accountability Office High Risk Series report from 2019 stated that NASA acquisition management has been on its high risk list since 1990 and regressed between 2017 and 2019 (Ref. 13). The report called out a skills gap in systems engineering and other areas.
   b. There is a risk of continued cost and schedule growth for major programs and projects.
5. The complexity of NASA missions and system of systems approaches in NASA missions and organizations is increasing.

A complex system comprises large numbers of strongly interacting elements that often have nonlinear behavior, multiple feedback loops, and changing or uncertain boundaries (Ref. 14). A system of systems has multiple components, each of which may be owned and operated by different entities, that combine to deliver the desired service or product. Although NASA is one entity at the Federal agency level, NASA has within it many organizational structures that are controlled and managed somewhat independently from each other. The aspects of complexity and systems of systems that are relevant to MBSE are listed here.

- Complexity:
  - The complexity of NASA missions is growing faster than our ability to manage it. Example missions are autonomous spacecraft and aircraft, launch vehicles, and crewed missions to distant, unexplored destinations.

    - The complexity of NASA missions and organizations makes communications with all stakeholders similarly complex.
- System of systems:
    - Missions and organizational structures are each system of systems.
    - Major missions have increasing numbers of interacting elements with uncertain boundaries, emerging behaviors, and unanticipated consequences.
    - Engineers have difficulty using traditional systems engineering and project management processes to develop, test, operate, and maintain these systems.
    - Multiple internal and external organizations are involved in programs, projects, and innovation initiatives.
    - Informal partnerships and leveraging can occur with unclear, overlapping lines of authority, responsibility, and access to information.

3.4 Strategic Advantages

The observations that were analyzed for strategic advantages specific to NASA are listed in the Appendix. The sources were mainly NASA interactions and reports and presentations by NASA leaders. Five major advantages emerged from the observations.

1. Missions to explore the unknowns in both our own planet and beyond, and travel to distant worlds provide motivation for the workforce and has high interest from the public.
2. NASA has an experienced workforce and world-class test and computational facilities.
3. NASA has and continues to accomplish difficult, complex missions with high uncertainty, international partnerships, and long durations.
4. NASA is using new partnerships with commercial industry and academia to accomplish its mission.
5. NASA is known as a national leader in technical innovation.

NASA has strategic advantages, beyond the ones listed here, that are specific to exploration, development, and use of MBSE. For more than a decade, hundreds of engineers have had hands-on use of MBSE on real projects and now form a “smart buyer” CoP with members from all NASA centers. During the MIAMI existence from 2016 to 2020, the MIAMI leaders sought to capture knowledge and lessons learned from the participants. The lessons learned that are applicable for when and how to implement MBSE on programs and projects to provide value added solutions to real NASA engineering problems were summarized in Reference 5. Additional suggestions of approaches for development of MBSE capabilities, project deployment, technology and methods evolution, and the change process and how to map those to an MBSE vision were presented in Reference 6. Through the MIAMI results and experiences, NASA has an understanding of change leadership, change processes, and partnerships for innovation and culture change, in addition to the technical aspects of MBSE.

3.5 Driving Forces

The observations that were analyzed for driving forces are listed in the Appendix. Eight driving forces were deemed to be most relevant to MBSE and are listed in Table 2 and shown in Figure 2 with ratings for each of their importance for MBSE growth and level of uncertainty.

TABLE 2.—KEY DRIVING FORCES FOR MODEL-BASED SYSTEMS ENGINEERING (MBSE)
[Also, legend for Figure 2.]

Label	Key driving force
A	Responding to new technology and the digital revolution
B	Motivation to explore through science and innovation
C	Change in national priorities
D	Competition in global economy for employees
E	Department of Defense and industry leadership in MBSE and digital engineering
F	Need for rapid and agile responses to the increase in complex, quickly changing environments
G	Barriers to change, cultural resistance
H	Skepticism arising from lack of evidence for the value proposition or return on investment for MBSE

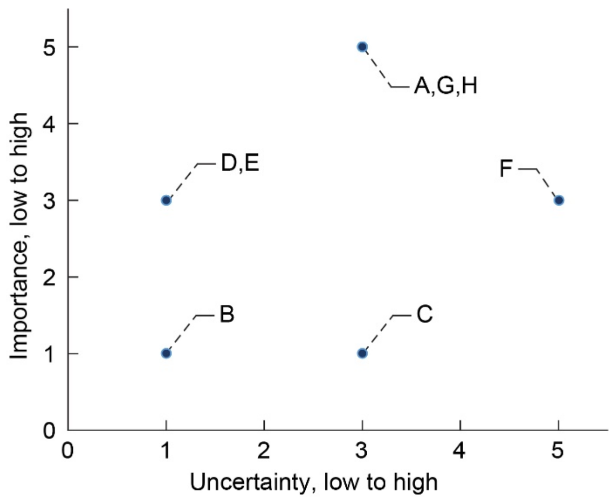

Figure 2.—Importance and uncertainty of key driving forces. Legend is in Table 2.

The world around us continues at an accelerating rate of change in new technology and the digital revolution. One recent example is a smartwatch with built-in health monitoring. What used to take specialized equipment and a trip to the doctor's office or hospital (electrocardiogram and blood oxygen level) can now be captured on your wrist. New technology and the digital revolution continue to open up opportunities for MBSE.

The DOD and industry leaders in MBSE and digital engineering drive the acquisition chain from service branches to suppliers of systems and their suppliers, along with software and service vendors, and academic institutions who provide education. Many of the DOD suppliers and vendors are also NASA's suppliers.

The increase in complex, quickly changing environments drives the examination of new approaches to doing traditional systems engineering, which are based on practices developed decades ago. The environment at NASA has changed significantly and new capabilities can be wielded for these environments.

Figure 2 provides different ways of determining a path forward. If an organization is considering an initiative in an area that is driven by a force with high uncertainty, it may wish to investigate and explore the area to understand the driving force and reduce the uncertainty. An organization may also choose to sponsor initiatives in high-impact, low-uncertainty areas. Low uncertainty does not mean it is easy to address the driving force; it means that the driving force is known.

3.6 Strategic Time Horizon

The initial timeframe considered for the future of MBSE at NASA was 20 years in the future, or 2039. After completing the analysis of context, challenges, and driving forces, it was apparent from the pace of change that the timeframe could be reduced to 10 years or less. The question was asked: what are NASA systems engineers doing in 2029 or next year?

4.0 Results

The future MBSE vision is presented as a summary with in-depth perspectives. The vision describes what NASA systems engineers and digital machines will do and how they will interact. A strategy bridge based on the Baldrige Criteria for Performance Excellence Framework provides recommendations for leaders and strategy and where investments of today would provide immediate and longer term benefits.

4.1 Future Model-Based Systems Engineering Vision—2029

The future MBSE vision statement is in three parts: (1) what the NASA systems engineer does, (2) what the digital machines do, and (3) what the NASA systems engineers and the digital machines do for NASA missions and what that means for NASA organizations. The vision statement conveys what it means to be a NASA systems engineer in the future and allows systems engineers to see themselves and envision their work activities. The vision statement allows systems engineers to see how they do their work with people and digital machines. And the vision statement tells systems engineers the reasons why they are doing their work, the NASA missions, and the infrastructure that enables the missions. Important attributes of the vision are depicted in Figure 3.

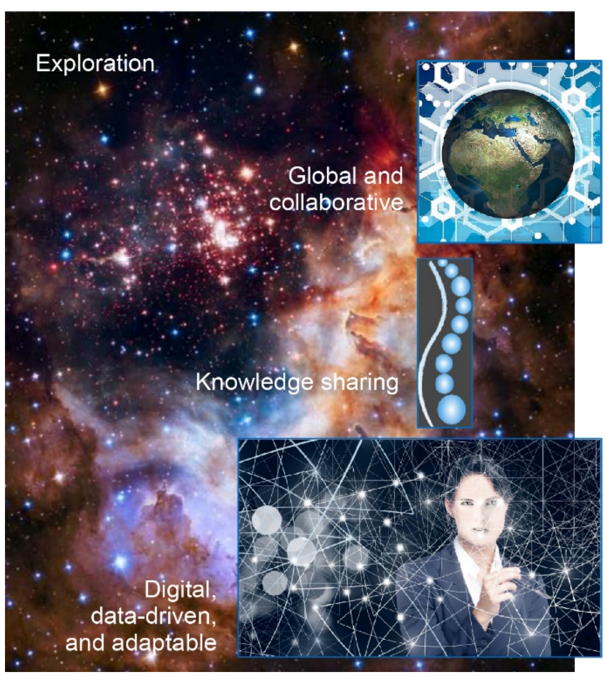

Figure 3.—Important attributes of future model-based systems engineering vision.

The vision statement has three main parts with supporting statements for each part.

1. The NASA systems engineer works with a global project team in a virtual and collaborative environment, engineers the system, and uses digital approaches as the routine and default way of working.
    a. NASA systems engineers work with many people on the project in a virtual, collaborative environment. The team is located around the globe and they are immersed in an environment that simulates their system of interest in operation. They have digital assistants, and they personalize their mixed-reality work environments. Learning is through personalized interactions with a knowledge-sharing infrastructure that provides knowledge and data when asked.
    b. NASA systems engineers "engineer the system" and design and develop at the system level to achieve the desired system performance. They provide the needs, concept of operations, and constraints, and guide digital machines to generate and optimize system architectures and designs. They use the digital machines to obtain deeper insights, do tradeoffs, and carry alternatives for design options until key decision points.
    c. NASA systems engineers use digital approaches as the routine and default way of executing the project. They use digital information, data, and models from many locations in a seamless way across the entire project life cycle. The NASA systems engineers develop, test, and operate a system of systems, that is, a large number of interacting elements with uncertain boundaries, emerging behaviors, and unanticipated consequences.
2. The digital machines provide data-driven and automated mission designs; have a backbone of program and project management, systems engineering, and product life-cycle management; and are a knowledge-sharing infrastructure.
    a. The digital machines provide data-driven, automated mission designs. Their computational power drives simulations and builds optimized designs. The digital machines know standards and guidelines and account for them.
    b. The digital machines have a backbone of program and project management, systems engineering, and product life-cycle management activities. The digital machines store and supply physics-based, human, social, and economic aspects of the system and its life-cycle management activities.
    c. Digital machines are a knowledge-sharing infrastructure. The machines provide information that the NASA systems engineer needs at the right time. The machines gather, retain, and provide information and the wisdom of pioneers to the NASA workforce.
3. The NASA systems engineer and the systems engineering team use digital machines to plan and perform rapid exploration missions, develop a digital twin that lasts across the life cycle, and develop enduring and adaptable systems. NASA has an engineering enterprise and a life-cycle management framework that endure, adapt, and respond.
    a. The NASA systems engineer and team use digital machines to plan and perform robotic and human exploration missions on and off planet Earth.
    b. The NASA systems engineer and team develop a digital twin that lasts across the life cycle. They use an integrated simulation of a system, including humans, that applies models, information, and input data to mirror and predict activities and performance over the life of

its corresponding physical twin. They share information across many disciplines and organizations by the computational and communications framework of a digital thread.

c. The NASA systems engineer and team develop systems that endure and adapt to complex and changing conditions. They respond rapidly with verified and validated solutions.
d. The NASA systems engineer and team use an engineering enterprise and a life-cycle management framework that also endure, adapt, and respond.

Figure 4 shows indications of the future. The strategy group anticipated that four forces—mission, people, technology, and place—will interplay. Human creativity integrates with machine capabilities, and engineers use system-focused, human-centered technologies to design bold, new missions. The graphics are from those prepared by the strategy group in 2019 (Ref. 3). Please refer to the publication for additional and more specific information.

The lower left panel of Figure 4 depicts how real-time collaboration with humans and digital machines allows team members to look at different views of the same system, and discuss them, at the same time. Each sees the aspects of the system that are of interest. This example shows two engineers viewing a vehicle, with one seeing dimensions and the other seeing stress calculations. This collaborative environment enables rapid interaction in a distributed, seamless way and provides the engineers with deeper insight into mission design requirements and constraints.

The top center panel of Figure 4 depicts how immersive simulation environments let an engineer observe the system in action in its intended environment. The example shows an engineer "viewing" the interior of a vehicle design. Another example is watching how a small launch vehicle launches from the surface of another planet, such as Mars. An immersive work environment lets individual engineers work where they want to be, in the forest or at the beach. New technologies and applications blur the boundaries of physical, digital, and biological worlds, and change the ways we live, work, interact, and communicate.

The lower right panel of Figure 4 depicts an engineer surfing the data ocean for data-driven work. The 1s and 0s in the data ocean and waves may be used for a model library, human-artificial intelligence collaboration, data-driven manufacturing, and dynamic testing.

Figure 4.—Aspects of future model-based systems engineering vision.

4.2 Future Model-Based Systems Engineering Vision—2029 Deeper Look

A deeper look at the future MBSE vision provides a thought-provoking, but not predictive, view of the future. Each part of the vision is considered in terms of what will be done in the future, what will not be done compared to today, and why should anyone care. Table 3 is about the NASA systems engineer in 2029. The easier and better ways in which a systems engineer will work are in the first column labeled "Will do in the future." The challenges that a systems engineer faces daily are in the column labeled "Will not do in the future that we do today." The expected benefits to the systems engineers are in the third column labeled "Why should I care?"

Table 4 is about the digital machines in 2029 and has three columns labeled the same as Table 3. The first column is what the digital machines will do in 2029. The second column is what NASA systems engineers will not do that the digital machines will do instead. The third column, again, provides reasons for why one should care. The information covers many of the needs and desires that systems engineers, managers, and educators have expressed based on their knowledge of what the digital machines can do currently and their projections into the future. The accelerating pace of development of digital machines, infrastructure, and software codes suggests that these capabilities may be available very soon. A systems engineer should have a mindset that is open to the new ways of working with digital machines, and let the machines do what they are good at and let the people do what they are good at.

Table 5 brings it all together for NASA missions in 2029. It shows how the NASA systems engineer uses digital machines to plan and perform NASA missions in 2029, and the engineering enterprise and life-cycle management framework. The three columns are labeled the same way as the previous tables.

TABLE 3.—NASA SYSTEMS ENGINEER IN 2029

Will do in the future	Will not do in the future that we do today	Why should I care?
Global project team	Siloed, disconnected, burdensome approaches for knowledge transfer among individuals in different organizations	Easier access to expertise from anywhere; better connections between areas of deep expertise (silos); and opportunity to work on interesting projects from any location
Virtual, collaborative environment[a]	Excessive travel or commute time	Spend more time doing engineering work that contributes to accomplishing NASA's missions
Immersive simulation of system of interest in operation	Testing that covers all possible conditions; large leaps of imagination	Easier to explore more of the option space; greater confidence that the design works as predicted; higher likelihood of optimal solution; and quicker understanding
Digital assistant	Spend time looking for documents and data	Spend more time doing engineering work that contributes to accomplishing NASA's missions
Engineers the system: automated generation and optimization of architectures and designs	Lock in prematurely on the design and rely solely on the knowledge of subject matter experts of components	Better access to broad knowledge base; easier to explore more of the option space; and higher likelihood of optimal solution
Digital approaches as routine and default way of working	Not Microsoft® Office™-based and messages from everywhere (email, chats)	On-demand, seamless, and integrated view of your work

[a]Face-to-face meetings and working in laboratories, test cells, and facilities have definite value and will continue. The work that can be done virtually will be done that way.

TABLE 4.—DIGITAL MACHINES IN 2029

Will do in the future	Will not do in the future that we do today	Why should I care?
Data-driven, automated mission designs	Design by separated individuals and teams	Less reliance on institutional memory and easier to explore design space beyond the imagination
Simulations and build optimized designs	Build and evaluate point designs; select the design early and cannot easily adjust to changing environments	Overall system is better optimized for desired performance, cost, schedule, and risk; assistance to make sound decisions by fully understanding the impact of changes to parameters and interfaces when the digital machine presents alternative
Know and account for standards and guidelines[a]	Manually select and assess compliance to standards and guidelines	Shortens time and reduces errors
Backbone of program and project management, systems engineering, and product life-cycle management[b]	Managers and engineers mentally synthesize separated information	Managers and engineers are presented more comprehensive and clearer integrated project views
Store and supply physics-based and social aspects[c]	Individual, physics-based aspects	Better understanding of how the system and its environment, including humans, interact
Knowledge-sharing infrastructure[d]	Process data and information into databases; track down the experts; and search the World Wide Web	Easier access to all of NASA's historical data; faster access to the right information at the right time; and reduces errors, which have led to past mishaps

[a]People tailor the standards appropriately.

[b]These disciplines serve as the underpinnings of NASA programs and projects and their life cycles from concepts through development, operations, and retirement. It is important to match the digital machines, in infrastructure and processes, with the ways in which NASA does business.

[c]Examples of physics-based aspects are structures, materials, heat transfer, optics, and chemical reactions. Examples of social aspects are how humans will use the systems, how accepting is the public of NASA's systems, how do the people at NASA interact to develop and operate the systems, and how do people at NASA share knowledge.

[d]Training will be more efficient and enjoyable through knowledge-sharing infrastructure and personalized interactions with the machine. There will be continuous data gathering and incremental learning.

TABLE 5.—NASA MISSIONS IN 2029

Will do in the future	Will not do in the future that we do today	Why should I care?
Plan and perform rapid exploration missions	Long time between brilliant idea and the mission or flight	NASA does rapid, extraordinary, and unprecedented missions
Develop a digital twin[a]	Functional models of hardware and software and individual analyses and simulations	Reduces the amount of scrap and rework and enables focused testing and evaluation at lower cost and less time
Mirror and predict performance over the life of the system	Time- or exposure-based maintenance and repair upon failure	Data-driven maintenance allows mission to intervene before failure
Share information across disciplines and organizations by a digital thread	Manually collect information from many sources and assess which is the right version to use	Shared, authoritative information available on demand to everyone on the project (NASA and partners)
Develop enduring and adaptable systems	Develop brittle systems for one purpose and discard or mothball systems because they are not easily adaptable or reusable	Easy reuse of existing systems for new or changing purposes and conditions
NASA engineering enterprise and life-cycle management framework endure and adapt	Large infrastructure changes to accommodate new methods and technology and years to decades behind in new technology	NASA missions reflect the flexibility and adaptability of our organizations and up-to-date systems compared to our suppliers and partners

[a]Analyses pull from an authoritative source of truth, so that all the analysts are looking at the same design at the same time.

The rest of this report provides recommendations for how NASA can start to attain this future. Many large and small changes are needed to attain this vision. The phrase “what you foresee, is what you get” expresses how expectations, strategic thinking, and approaches used for innovation such as design thinking, may help NASA determine how to get to the future vision, what NASA should do, and who should lead (Ref. 15).

4.3 Model-Based Systems Engineering Strategy Bridge

The anticipated changes have significant complexity with multiple disciplines and rapidly evolving technologies. Within NASA, there are many organizations and individuals with responsibility and influence that could be part of realizing the future MBSE vision. From 2016 to September 2020, the NASA Engineering and Safety Center Systems Engineering Technical Discipline Team led MBSE for the Agency through its sponsorship of MIAMI. The top lessons learned were captured near the end of MIAMI (Ref. 5). The Agency MBSE CoP continues on and leads the user community to learn, develop, and advance MBSE. The Agency MBSE CoP interacts with center-level groups, often at the user level. An Agency MBSE Leadership Team was formed that took over the leadership of MBSE for the Agency from MIAMI. Each NASA center has a representative on this team. NASA established a Business Innovation Office to lead its digital transformation. One of the six digital thrust areas, that of Model-Based X, has MBSE as part of the thrust area, as are model-based mission assurance and model-based project management and others. The remaining five digital thrust areas, those of artificial intelligence and machine learning, collaboration, culture and workforce, data, and process transformation, all have a role in realizing the future MBSE vision. The Digital Transformation team has representatives from NASA centers, mission directorates, and mission support areas. There are also external entities in other Government agencies, industry, and academia who are advancing MBSE. Many of these entities and individuals engage in professional societies, working groups, and standards organizations.

Because of the number of disciplines, rapidly evolving technologies, and numbers of organizations involved, a strategy bridge from today to the future is needed. The strategy bridge organizes the “what” NASA should do, and the characteristics of “who should lead.” The strategy bridge from today to the future needs enough structure to close the gaps and to be flexible and adaptable.

The Baldrige Criteria for Performance Excellence Framework (Ref. 7), as shown in Figure 5, is one approach for a strategy bridge and is used here. The framework provides a way for an organization to examine its adherence to core values and concepts, such as valuing people, visionary leadership, customer-focused excellence, and more. It also provides a way for an organization to examine how its core values and concepts are embedded in its processes for leadership, strategy, customers, measurement, analysis, and knowledge management, workforce, and operations. The framework provides a way for an organization to examine how the processes yield results in the areas of financial, leadership, products, the workforce, and more. The results are represented at the top of the cylinder in the right-most hexagon.

The organizational profile aspects of leadership and strategy were considered first and are summarized in Table 6. The left column of the table lists what leaders should do and what they need to know. The right column of the table lists important aspects of a strategy for obtaining the future MBSE vision.

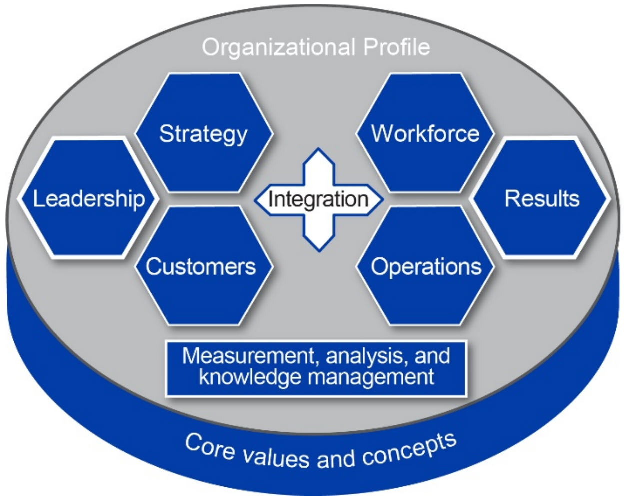

Figure 5.—Baldrige Criteria for Performance Excellence Framework (Ref. 7) (Credit: Adapted from Baldrige Performance Excellence Program. 2021. 2021–2022 Baldrige Excellence Framework: Proven Leadership and Management Practices for High Performance. Gaithersburg, MD: U.S. Department of Commerce, National Institute of Standards and Technology. https://www.nist.gov/baldrige.)

TABLE 6.—BRIDGING THE GAP WITH LEADERS AND STRATEGY

Leaders	Strategy
• Understand and communicate a big-picture, long-term vision • Express clear expectations • Demonstrate organizational commitment to model-based systems engineering (MBSE); • Engage with the workforce, partners, and customers to produce results • Leverage lessons learned from the workforce and Agency and local MBSE leaders • Balance short-term demands with long-term investments • Knowledgeable about MBSE, and implementation approaches for culture change and new technology • Knowledgeable about digital engineering, digital twin, and more	• Provide a framework to lead and manage future MBSE as a unified whole • Provide a supportive environment, processes, and resources that encourage innovation • Allow for significant and rapid change, agility, and flexibility in approaches • Minimize disruption of critical and essential missions and services • Tap into workforce motivation and competence, test and computational facilities, and partnership experience • Show the value of MBSE and gain advocates along the way

The leaders in Table 6 are the people who lead Agency and center-level groups and organizations with responsibility and authority to advance MBSE. The leaders are also members of the workforce in any organizational level or role. The workforce members help leaders by filling in knowledge gaps, being open about their experiences and concerns, and communicating with their peers. Workforce members help leaders by asking the right questions, such as what is your big-picture and long-term vision? what are your expectations of me in this area? and how can I help you, help all of us? The leaders and workforce members can do their parts by learning more about MBSE, new technology, and culture change as a place to start. Each person has strengths and weaknesses, and together, the leaders and members have the collective knowledge and leadership for success.

The aspects of the strategy listed here are relevant to the operating environment, leverage the organization's strengths, and recognize the challenges of innovation and change leadership. Each of these was used during MIAMI (Refs. 2 to 6). This recommended strategy builds upon the successes of MIAMI towards realizing the future MBSE vision. In addition, the MIAMI leaders adapted and applied concepts and tools from design thinking, lean startup, high-technology marketing, and change leadership (Refs. 15 to 18).

A strategy is more than the vision; it is how the vision is realized in terms of organizational environment, approach, and resource allocation. The details and specifics are in the tactics. It should have insight into the current and future contexts and contain decisions on goals and objectives. Milestones and plans for its implementation can be tracked, evaluated, and adjusted. A strategy should consider how to implement changes without disrupting critical and essential missions and services. It is undesirable for it to stop NASA missions for months to years for changes. It may be useful for the long timeframes of decades or short timeframes of months to years. The time duration for a strategy depends on the strategic time horizon. It will need regular tuneups, such as quarterly. Lastly, a strategy is as much about what is chosen not to do as much as what is chosen to do. Deliberate decisions on where the organization focuses its efforts and resources mean that not everything can be done nor should it.

The organizational profile aspects for customers; workforce; operations; and measurement, analysis, and knowledge management were considered next. Recommendations for investments that would provide immediate benefits are summarized in Table 7. Leaders and their strategy will drive the selection and priority of investments in these profile aspects.

Recommendations for investments of today that would provide benefits in 2029 or earlier are summarized in Table 8. The future will arrive sooner than we perceive, and industry partners are moving this way very quickly. Leaders and their strategy will drive the selection and priority of investments in these profile aspects.

TABLE 7.—INVESTMENTS OF TODAY FOR IMMEDIATE BENEFITS

Measurement, analysis, and knowledge management[a]	Customers[b]	Workforce[c]	Operations and processes[d]
• Digital knowledge sharing infrastructure • Ways to measure and analyze meaningful performance improvement data	Program and project managers, systems engineers, and product life-cycle managers are satisfied	• Engaged in future model-based systems engineering (MBSE) planning and implementation • Trained and upskilled workers • Stay on the job with workforce retention policies and incentives	• Virtual, collaborative environment • Work processes that improve workforce performance and reduce errors

[a]The metrics by which success is evaluated through performance improvement data will drive behavior and may result in unintended consequences.

[b]Involve program and project managers, systems engineers, and product life-cycle managers to understand their needs and what will satisfy them. You will have happy stakeholders, and they will tell their friends.

[c]Invest in training and upskilling workers, even for those who may appear less able to learn MBSE. Many of NASA's best MBSE modelers are later-career employees. Workforce retention policies and incentives help convince a skilled workforce to stay on the job.

[d]The virtual, collaborative environment builds upon what became so essential for NASA in 2020 and 2021 during the global COVID pandemic.

TABLE 8.—INVESTMENTS OF TODAY FOR 2029

Measurement, analysis, and knowledge management	Customers	Workforce	Operations and processes
• Digital knowledge and accounting for standards and guidelines • Digital, data-driven, automated mission designs • Digital system simulations and optimized designs including digital twin	• Have access to information across disciplines and organizations by a digital thread • Access physics-based and social aspects of their system before completion	• Receive performance incentives for digital approaches • Work from anywhere under policies for a global project team • Dedicated workforce with competencies beyond day-to-day work	• Digital approaches as routine and default way of working • Develop enduring and adaptable systems

5.0 Application of Lessons Learned From Modeled-Based Systems Engineering Infusion and Modernization Initiative

From 2016 through 2020, over 200 participants on MIAMI captured important lessons learned. These were highlighted in the NASA Engineering and Safety Center webinar on October 14, 2020, by Jessica Knizhnik, on "MBSE to MIAMI to Implementation, an Overview" and are in References 4 and 5. These lessons learned, along with experiences in leading a change initiative, are described here for their application to the future MBSE vision and strategy bridge.

- Do things with a purpose and to solve a problem. Consider ways to bring together the multiple disciplines and organizations needed for the future MBSE vision. A problem-based challenge, similar to the Defense Advanced Research Projects Agency (DARPA) Grand Challenge for an autonomous vehicle, could bring together people from a broad spectrum of disciplines and create the conditions for rapid development and engagement (Ref. 19).
- Do things slowly and steadily. A good approach is to evolve, take small steps, test a little, learn, iterate or pivot, and build. Do not boil the ocean to start, instead first boil water for the teacup and grow. Point your efforts to the big change and you will get there.
- Find the bold, committed leaders, and give them authority and resources. This demonstrates organizational commitment and empowers the leaders for real action. The leaders then empower people at lower levels who understand and are guided by the vision.
- Use new ways of thinking to look at the problem in new ways. Use and adapt approaches from other disciplines, such as the design and business worlds, to your advantage. Design thinking, lean startup, high technology marketing, strategic thinking, and others can assist you in reframing and solving your problems.
- Engage and reengage with stakeholders, especially with those most impacted by the future MBSE vision. There are many changes in processes, skills, the use of technology, and infrastructure associated with this vision. Any approach needs to acknowledge that there are parts of the future MBSE vision that make people uncomfortable. Keep at the forefront the needs of the users.

The barriers to change are real and must be acknowledged. The main ones are cultural resistance to change, difficulties with the software tools, and the insufficient pipeline and training of systems engineers with skills in these areas. These barriers may be overcome with knowledgeable and committed leaders; more and improved training; and designated responsibilities and roles for MBSE in the NASA organizations.

6.0 Concluding Remarks

A future model-based systems engineering (MBSE) vision shows what NASA systems engineers and the digital machines do to perform rapid, extraordinary, and unprecedented missions in 2029. The NASA systems engineer works with a global project team in a virtual and collaborative environment, engineers the system, and uses digital approaches as the routine and default way of working. The digital machines provide data-driven and automated mission designs; have a backbone of program and project management, systems engineering, and product life-cycle management; and are a knowledge-sharing infrastructure. The NASA systems engineer and the systems engineering team use digital machines to plan and perform rapid exploration missions, develop a digital twin that lasts across the life cycle, and develop enduring and adaptable systems. NASA has an engineering enterprise and a life-cycle management framework that endures, adapts, and responds.

A strategy bridge illuminates a way from today to a desired future and how MBSE adoption can be more rapid with committed leaders and managers with authority and resources to establish a long-term capability.

Appendix—Future Model-Based Systems Engineering Sources and Observations

Table 9 contains a list of publications, reports, and presentations from which observations about model-based systems engineering have been made. These observations are broken down by the type of organization the observation is from and indicate each category the observation would fulfill. The following list indicates the tables by organization.

- Table 10: academia
- Table 11: industry
- Table 12: NASA
- Table 13: other Government agencies
- Table 14: professional societies
- Table 15: software vendors

TABLE 9.—FUTURE MODEL-BASED SYSTEMS ENGINEERING SOURCES

Citation number	Publication
1	Bajwa, Anupa R., et al.: Strategic Perspectives on the Future of Systems Engineering at NASA. NASA/TM-20205002911, 2020. https://ntrs.nasa.gov
2	Pawlikowsi, G.: Independent Assessment of Perception From External/Non-NASA Systems Engineering (SE) Sources. Report Submitted to NASA Tech Fellow for SE, 2020.
3	NASA Model-Based Systems Engineering Community of Practice. Future MBSE Channel of MBSE CoP, MS Team Chat, Download 2020-08-17, 2020.
4	Department of Defense: Digital Engineering Strategy. Office of the Deputy Assistant Secretary of Defense for Systems Engineering, 2018.
5	International Council on Systems Engineering: State of the Discipline. 2019.
6	Huldt, T.; and Stenius, I.: State-of-Practice Survey of Model-Based Systems Engineering. Systems Engineering, 2018, pp. 1–12.
7	Watson, M.D.: Future of Systems Engineering. INCOSE Insight, vol. 22, no. 1, 2019, pp. 8–12.
8	Watson, M.D.: Systems Engineering Principles and Hypotheses. INCOSE Insight, vol. 22, no. 1, 2019, pp. 18–28.
9	Mordecai, Y.; and Dori, D.: Towards a Quantitative Framework for Evaluating the Expressive Power of Conceptual System Models. INCOSE Insight, vol. 21, no. 1, 2018, pp. 28–37.
10	Peterson, T.: Systems Engineering: Cracking the Code of Digital Transformation. INCOSE Insight, vol. 22, no. 1, 2019, pp. 29–31.
11	Ryan, M.: On the Use of Perspective in Managing Complexity. INCOSE Insight, vol. 21, no. 1, 2018, pp. 38–41.
12	Stoewer, H.; and Lin, C.: Results from the Panel on MBSE Transition Towards the Digital Enterprise—Where Do We Go From Here? INCOSE Insight, vol. 22, no. 1, 2019, pp. 51–53.
13	West, T.D.; and Blackburn, M.: Demonstrated Benefits of a Nascent Digital Twin. INCOSE Insight, vol. 21, no. 1, 2018, pp. 43–47.
14	McDermott, T.; and Salado, A.: Art and Architecture: Effectively Communicating Models of Systems. Proceedings of the 2018 Annual IEEE International Systems Conference, Vancouver, Canada, 2018. https://ieeexplore.ieee.org/document/8369605
15	Hale, J.P., et al.: Digital Model-Based Engineering: Expectations, Prerequisites, and Challenges of Infusion. NASA/TM—2017-219633, 2017. https://ntrs.nasa.gov
16	Madni, A.; and Sievers, M.: Model-Based Systems Engineering: Motivation, Current Status, and Research Opportunities. Syst. Eng., vol. 21, 2018, pp. 172–190.
17	Holladay, J.; and Crumbley, T.: SE Strategic Vector. Draft presentation, 2018.

TABLE 10.—FUTURE MODEL-BASED SYSTEMS ENGINEERING (MBSE) OBSERVATIONS: ACADEMIA
[Stakeholder analysis (SA). Strategic challenges (SC). Strategic advantages (SAD). Key driving forces (KDF). Future MBSE vision (FMV).]

Citation	Observations	SA	SC	SAD	KDF	FMV
2	Source has a digital manufacturing and design (DMD) perspective; is involved with Coursera Inc. DMD and MBSE courses, and an Industrial Systems Engineering Department, dealing with industry systems.	X				
2	Source co-authored the book titled *Effective Model-Based Systems Engineering*.	X				
2	Source has taught short courses on Systems Modeling Language (SysML) and how to model with No Magic (Dassault Systemes) at most NASA Centers and currently at Naval Air Systems Command (NAVAIR).	X				
2	We offer a systems engineer (SE) Master’s and Doctor of Philosophy degrees and a SE certificate with MBSE and SysML courses.	X				
2	Source has a computer science course that teaches students how to build MBSE tools.	X				
2	“I do not believe SysML is that scalable and cannot do formal reasoning, so we have been going down a road to replace SysML with building ontologies and infrastructure semantic digital twins.”				X	X
2	MBSE will be replaced by digital twin because SysML by itself is only useful for the front end of product development life cycle.				X	X
2	Model-based engineering (MBE) will have to find its way into courses for bachelor’s degrees and below.	X				
2	A key challenge with making systems engineering faster and more efficient is dealing with cultural issues and change.		X		X	
2	A key challenge in adopting MBSE is adequate training; if we are not training them until they get their Master’s, we are not infusing MBSE enough into the culture.	X	X		X	
6	There is a need to increase the capabilities to perform model-based approaches on a greater scale, for example, life-cycle, program, and portfolio management.					X
6	Latter parts of the systems engineering life cycle need further development of MBSE applications, methods, and notations, to support, for example, risk management, technical reviews, and verification and validation (V&V).					
6	The main inhibitors include cultural hurdles, the MBSE learning curve, and availability of skills.	X	X		X	
6	An inhibitor is due to cultural and general issues.		X		X	
6	An inhibitor is the lack of perceived value of MBSE.				X	
6	An inhibitor is the availability of skills.	X			X	
6	An inhibitor is the lack of management support.	X	X		X	
6	An inhibitor is the MBSE learning curve.					
6	Inhibitors can most likely be significantly reduced if management, training, and structures are improved, which again is a matter for the organization's management.	X	X		X	
6	Organizations that have not addressed these issues (hurdles) at the appropriate management level (e.g., choosing to delegate authority and resources to lower levels of management) have failed to establish a long-term capability.	X	X		X	
6	A successful implementation of a model-based approach is a management issue that can only be resolved through a clear and committed leadership. This requires that managers have the relevant understanding and competence.	X	X		X	

TABLE 10.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
6	However, systems engineering tools are not generally applied in a wider context to support collaborative environments to integrate different technical domains. The consequence will most likely be that the full potential of introducing an MBSE approach is not reached, and the effects are typically constrained to the systems engineering domain.					X
6	Of the responders, 61 percent thought improved organizational structures would be the preferred means of improving an MBSE approach, while 21 percent thought training and education, 14 percent thought tools and infrastructure, and 5 percent thought process and methods.	X	X		X	
6	Systems engineering is a relatively young discipline and there are no well-established methods on how to measure its benefits on a larger organizational scale. This will also have an impact on how MBSE is perceived and validated.				X	
6	Well-defined and largely deployed methodologies and standards, for example, SysML, could increase the ability to evaluate systems engineering in general and thereby support a more accurate manner on how to verify its value.				X	X
6	An area to improve is the lack of strong management structures to support and guide the implementation, from higher echelons and down to its execution.		X		X	
6	An area to improve is the lack of understanding of what MBSE is and what value it brings				X	
6	An area to improve is the lack of knowledge to integrate a model-based approach with current business processes.	X	X			
6	An area to improve is the lack of available trained resources.	X	X			
6	There is a need for further development for the MBSE approach, supporting how to manage a successful implementation rather than improving its execution.		X			
6	Management levels need to be trained and educated in the topic in order to increase the knowledge and understanding of what it is and its value, in order to clearly guide and control an effective implementation.	X	X		X	
6	There is a need to further strengthen and develop how an MBSE approach should be introduced and managed to be able to utilize the full potential of MBSE.		X			
9	We introduce MIA—Model Informativity Analysis—a quantitative, utility-based, prescriptive approach for boosting conceptual models' expressive power and measuring the value of the information they provide.					X
9	Progress is underway in the area of knowledge-based design automation.					X
9	We also study the improvement in informativity of protocol and standard models as part of transitioning to a model-based standard and protocol authoring.					X
11	Researchers can readily show that the perceived complexity of an entity under consideration can vary dramatically if they take different perspectives.		X		X	
11	We need to have two different perspectives: first, the system of systems (SoS) perspective, which describes what each SoS will do, the constituent elements that are present, and what the SoS expects of each of the constituent systems in that SoS, and second, the system perspective, which describes what the system itself does and what interfaces are required for the system to allow it to belong to each of the SoS for which it is required to be a constituent element.		X			
13	A truly perfect digital twin model is both infeasible and impractical in the near term. Imperfect digital twin models and related "disruptive" technologies showed 30 percent cost reductions and 25 percent weight reductions in industry and Department of Defense (DOD).		X		X	

TABLE 10.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
13	DOD defines digital twin as an “integrated multiphysics, multiscale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities and performance over the life of its corresponding physical twin.”					X
13	Our concern was that, by overpromising on what such tools could deliver in the near term, the community risks losing the strong advocacy it has attained at the highest level of DOD if we fail to deliver on those promises. The goal of that paper was to add perspective during this second phase of Gartner’s hype cycle in order to more effectively manage expectations of what digital engineering could soon deliver.	X	X		X	
13	Although we still maintain that the realization of a digital twin technology with perfect fidelity is decades into the future, many excellent works across the community continue to prove that a model does not have to be perfect to be highly effective in reducing the amount of scrap and rework that occurs in the development process, enabling more focused test and evaluation, and facilitating more streamlined system sustainment.				X	X
13	The Air Force teamed with the National Defense Industrial Association (NDIA) to convene three workshops with representatives from across government and the defense industry to discuss the challenges associated with creating a “digital ecosystem,” the necessary tools and technologies needed to develop such an ecosystem, and the changes to the acquisition rules and regulation to better facilitate the use of this ecosystem.	X	X		X	X
13	Our prior paper raised concerns with the time and talent required to develop robust models, highlighting the need to develop a model-savvy workforce to support the digital transformation. A recognized assumption in the paper was an extrapolation of historical software development rates for an unprecedentedly large software development effort. However, multiple factors could dramatically reduce the software development rate and increase the national pool of software developers. Light Table (Kodowa, Inc.) and the Safety-Critical Application Development Environment (SCADE) (Ansys, Inc.) are examples.	X			X	
13	The Ansys, Inc., SCADE, which offers a “model-based development environment for critical embedded software,” is already transforming how Subaru, Piaggio Aerospace, Airbus, and similar companies design and validate code in their cyber-physical systems.		X			
13	Artificial intelligence (AI), when coupled with requirements pseudocodes and automatic code generation, promise to accelerate the model process even more.					
13	The Government may not need exclusive ownership of the digital twin to reap its benefits. An example is the Naval Sea Systems Command (NAVSEA) and Huntington Ingalls Industries, Inc., data model.	X				
14	We further explore three core methods—composition, abstraction, and communicating and focusing—that the architect uses to convey their vision.					X
14	Four Noise Killing (NK) strategies to aid the artist or architect in decomposing and recomposing a complex system or situation in order to effectively convey the quality or goodness of selected solutions are to subtract details, symmetry, to list and group, and to split. NKs are analysis methods.		X		X	

TABLE 10.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
14	Four Meaning Adding (MA) strategies that aid the artist or architect in decomposing and recomposing a complex system or situation in order to effectively convey the quality or goodness of selected solutions are to emphasize, to remix and reconnect, power of the center, and to contrast and balance. MAs are synthesis methods.				X	
14	They share a common theme of communication: NK strategies help to simplify the system to explain it, and MA strategies help to capture abstractions that communicate the complexity without overwhelming the observer.		X		X	X
14	Being able to align the system architect's internal context for their decisions and the external context of goodness for the stakeholders is the critical gap in communicating models of architecture.	X				X
14	In engineering today, architects learn tools to document their internal perspectives of the architecture but are seldom taught to express their internal context in forms that are meaningful to other stakeholders.					
14	Good architects use visual models that employ similar MA strategies as artists: using symmetry to visualize general system archetypes that portray balance, or lack of symmetry to portray imbalances; employing visual references with color, contrast, or other emphases to highlight central effects; and centering concepts around different themes to help simplify and reduce complexity.		X		X	X
14	There are typically two different languages a system architect must learn to speak. One, which is referential, reflects the context of the stakeholder needs and solutions. The other one, which is methodological, reflects the tools used to represent the model formally. Engineers who are well trained in analytical and methodological practices must develop the conceptual and compositional skills needed to communicate conceptually with stakeholders.	X				X
14	Mastering creative thinking is an essential part of systems thinking and systems architecture. In our experience, inelegant solutions often result from inability of engineers and senior decision makers to communicate their joint desires. Learning across three disciplines of art, systems thinking, and system architecture provides an effective background to improve these skills. At the core of such learning outcomes are proper use of composition.					X
14	As complexity increases, the communications gap between system modelers and decision makers continues to grow.	X	X		X	X
14	With nontechnical stakeholders, the methodological aspects of a tool language become noise because they are far outside their domains.	X				X
16	MBSE is a holistic, systems engineering approach centered on the evolving system model, which serves as the "sole source of truth" about the system. It comprises system specification, design, validation, and configuration management.					X
16	The systems engineering community has turned to MBSE to manage complexity, maintain consistency, and assure traceability during system development.	X	X		X	
16	The model embodies multiple complementary, mutually compatible perspectives. Typically, multiple perspectives are needed to answer stakeholder questions. This is in sharp contrast to engineering with models, where multiple models are employed, often with inconsistent assumptions and underlying semantics.	X				X
16	Engineers have used models in a variety of forms for centuries, while "engineering with models" has been an integral part of the engineering profession for decades. However, the increasing scale and complexity of systems have caused SE to rethink the approach to systems development.		X		X	

TABLE 10.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
16	The value of MBSE stems from the fact that all system-related information is stored and configuration-managed in a central repository. This characteristic enables the interconnection of model elements, effective information retrieval, and reasoning about the system. This interconnectivity also enables automatic propagation of design changes, consistency checking, and error identification.				X	X
16	In large organizations, maintaining a shared context is especially important for meaningful collaboration.	X				X
16	Having a clear representation of needs is a prerequisite to meaningful discussions about their relative importance and merits.					
16	With model-based approaches, documents that reflect the state of system development can be automatically generated from the model for the different stakeholders.					
16	An implied assumption in modeling is that model validation scope is defined with respect to the objectives of the model. In this regard, Active Nonlinear Tests (ANTs), a promising V&V technique, explicitly formulates a set of mathematical tests to “break the model.” Each time a model fails a validation test, it is modified until it passes the test. This iterative process builds confidence in model validity.					
16	Although there are strong benefits to using a common repository for all model content (e.g., to generate seamless views from the model for each stakeholder), there are significant challenges as well (e.g., different representational needs for different technical domains). Therefore, many organizations instead opt for a federated model concept, to address the challenge of heterogeneous representation of information.	X				X
16	This concept and approach (federated model concept) can work well if the different repositories containing model information are kept consistent and synchronized.					X
16	Current modeling approaches can be roughly classified into those supporting graphical representations and those supporting both graphical and semantic representations.					
16	Unified Modeling Language (UML®) (Object Management Group®, Inc.) and SysML have flexible semantics that enable rendering models in ways tailorable for different purposes. However, a fair criticism is that this flexibility also contributes to ambiguity, that is, there can be situations in which the meaning of diagrams or how the model operates may not be clear or may depend on the tool used to interpret the model.					
16	Object Process Methodology (OPM) comprises a small set of building blocks consisting of objects (an entity that exists for a finite time and exists in one or more states) and links (structural and procedural). Structural links show how objects relate to each other while procedural links connect processes to objects.					
16	Semantic representations provide models of computation, that is, rules governing execution of and interaction between model components. Examples include Foundational Unified Modeling Language™ (fUML), Ptolemy, State Analysis, Modeling and Analysis of Real-Time and Embedded Systems (MARTE), Design Structure Matrix (DSM), Lustre® (OpenSFS and European Open File System), and SCADE models. These semantic representations each have human-interpretable graphical representations.					
16	fUML and its associated Action Language for fUML (ALF) are a directly executable, rigorous semantic, subset of UML®.					
16	Ptolemy, another modeling tool, was developed to rigorously model heterogeneous, real-time, embedded systems using super-dense time in which time is divided into microsteps within a time continuum.					

TABLE 10.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
16	State analysis is a formal process for identifying and modeling system states and state relationships in control systems.					
16	The MARTE profile is an extension of UML® that supports the development and analysis of real-time hardware and software systems.					
16	DSM is an n × n matrix in which rows and columns represent the components and activities within a system. The matrix enables quickly identifying which functions depend on results from which other functions.					
16	Lustre® is a formally defined, declarative, and synchronous dataflow programming language intended for reactive, cyclic programs.					
16	SCADE comprises a graphical tool suite that supports software analyses, design, verification, and autogeneration for Lustre®.					
16	A model-based V&V approach, shown in Figure 7, mitigates several shortcomings of the “V” by using system models to begin the V&V process.					
16	Decomposition of each requirement on the left is accompanied by a more detailed model along with several test cases initially used for model V&V. Importantly, Figure 8 shows that test cases developed at a given iteration are used as regression tests at the next level. Moreover, tests developed during model development are applied on the right-hand side of the “V” allowing comparison of model and physical system results... that the results of each design iteration are checked before moving on to the next iteration. Equally important is the fact that testing is considered during the requirements decomposition phase, not as an afterthought.					
16	It may also be the case that the design effort proceeds at different rates or the verification of some requirements may not require detailed models of the entire system. The modified model-based V&V accommodates this range of concerns by allowing certain aspects of the system to be abstracted (“selective abstraction”) while focusing on issues that are of interest to stakeholders.					
16	Model-based V&V activities encompass several complementary and synergistic approaches: model appraisal; guided modeling, simulation; formal proof; and digital twin and digital thread.					X
16	Model Appraisal involves domain experts, ...assessing the quality of a system model.					
16	Guided modeling assists system modelers (i.e., system designers) in system of interest (SOI) modeling. Guided modeling comprises pattern-based approaches, template-driven approaches, and feedback-enabled approaches.		X			X
16	Simulation involves executing models of the SOI to explore the behavior of the system, uncover issues (e.g., constraint violations, performance shortfalls), update SOI models in the light of the feedback and rerun the simulations.					X
16	Formal proof is based on formal methods, languages, and tools. Formal methods are mathematics and logic methods to specify, develop, and verify systems.					
16	A digital twin is a digital version of a system that can be used for verification.					X
16	A digital thread comprises the computation and communications framework enabling sharing of information among siloed viewpoints that are common in multiagency, multicompany, multideveloper environments.					X

TABLE 10.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
16	The fundamental challenge to widescale MBSE adoption is gaining wide acceptance in the systems acquisition and program management communities. Because MBSE does not readily fit the traditional “documentation and review” paradigm that most customers are accustomed to, the move to MBSE requires a cultural change during system development.	X	X		X	
16	There is a noticeable gap in the documentation produced from models and what customers are accustomed to today. Also, while training can be expected to reduce reliance on traditional systems engineering artifacts, a subset of these will always be needed.	X				
16	MBSE needs to incorporate artifacts and objects that are maintained outside the MBSE database.					
16	What constitutes a complete set of models is a fundamental gap that is beyond the purview of MBSE. Also, the specification of model uses and how to use models is an overarching concern for model-based approaches.					
16	Then there are MBSE-specific issues. For example, is it possible to have a single, unified model? If not, how should different heterogeneous models communicate? How should different disciplines and attendant models interact with each other? What measures need to be taken to assure common assumptions and consistent semantics across different models from the different disciplines? How should quality attributes be incorporated in system models and how can the models be analyzed in terms of the degree to which they satisfy the quality attributes? What is the best way to capture knowledge, decisions, decision rationale, and expertise of system engineers? Last, since a model is a shared, living representation of multiple domains of interest, how can a consistent “baseline” be established, and how should it be reviewed?					X
16	Importantly, complex systems pose even greater challenges to systems engineering, whether done following a traditional document-based approach or a model-based approach. Complex systems typically comprise large numbers of strongly interacting elements (i.e., agents, processes). To understand these interactions requires nonlinear modeling methods and new tools. These characteristics (e.g., nonlinear behavior, multiple feedback loops, and changing or uncertain boundaries) make complex systems difficult to validate, test, and evaluate.		X	X	X	X
16	The gaps in MBSE methodology and immaturity of associated tools limit the breadth and depth of system reasoning, requirement elicitation, tradeoff analyses, V&V, and collaboration that we can achieve.					X
16	Extensive work has been done at the boundary of systems architecting and MBSE, in particular, investigating the importance of patterns in systems engineering of complex systems.		X		X	
16	Blackburn and his collaborators, under Systems Engineering Research Center sponsorship, have been working on assessing the technical feasibility of creating and leveraging a more holistic MBSE approach. In addition to his group’s research addressing various MBSE challenges including model management, model transformation, and consistency checking.					
16	Young et al. are investigating how to close the culture chasm in defense space applications of MBSE.		X		X	
16	Paredis has also laid out a roadmap for academic research in MBSE.	X				
16	Bock has investigated the use of SysML and UML® 2.0 for MBSE.					
16	Johnson et al. are conducting research on integrating models and simulations of continuous dynamics into SysML.					X

TABLE 10.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
16	A particularly challenging issue for MBSE is finding ways to reach a wider, and often nontechnical, stakeholder community. MBSE needs to add visualization and experiential viewpoints, so that nonexpert stakeholders can understand the models and provide timely and meaningful feedback.	X				X
16	There is ongoing research in interactive storytelling-enabled experiential perspective and experiential design languages.					
16	Another key research advance that needs to occur is augmenting MBSE with descriptive and analytic models of humans.					X
16	Interactive Epoch-Era Analysis (EEA), which investigates systems under dynamic uncertainty using a time-based description in which the system is evaluated through a series of stochastically changing static contexts; Model-Centric Decision Making, which examines how stakeholders interact with models, how trust in models can degrade, and how heuristics and guidelines for model-centric policies and practices can be developed; Framing Multistakeholder Tradespace Exploration, which focuses on eliciting inputs from stakeholders who cannot or will not express concerns and preferences in a standardized format; and Curation of Model-Centric Environments, which addresses the management of complex models.		X		X	X
16	Complex systems modeling methods include matrix methods such as DSM Engineering System Multiple Domain Matrix (ES–MDM), Change Propagation Analysis, and Dynamic ES–MDM. MBSE can be augmented with these approaches to strengthen the capabilities for dependencies and interaction analysis.		X		X	
16	Visual analytics is a related area of research that evaluates large design spaces enabling early removal of unacceptable design alternatives while continuing with promising options.					
16	A particularly powerful feature of open model-based environment (OMBE) (Open Model Based Engineering Environment, OpenMBEE) is its ability to aggregate information from heterogeneous sources into a linked data architecture.					X
16	MBSE can guide test planners in developing test strategies and detailed test designs for evaluating technical performance parameters. As tests are performed and data collected, the physical models can be updated with test data. The updated models can be evaluated through simulation to determine if the system model meets user requirements.					X
16	MBSE may need to be more broadly defined as MBE to address the cyber, physical, and human/social elements of the system. This broader perspective can make MBE the preferred approach for cyber–physical–social systems modeling, analysis, and design.	X				X
16	A recent International Council on Systems Engineering (INCOSE) MBSE workshop keynote prognosticated that MBSE will advance first and fast along the “hard” (i.e., physics-based) engineering aspects and subsequently integrate with the “soft” (i.e., human, social, economic, and environmental) aspects that influence systems engineering.	X				X
16	Management must enthusiastically get behind the cultural change implied by MBSE. The current culture of relying on document-centric systems engineering is arguably the most serious impediment to adopting MBSE in most organizations.	X	X		X	
16	There is a need for the acquisition community to move beyond traditional documentation and review paradigm to which government customers have become accustomed. For industry management to get more enthusiastically behind the cultural change implied by MBSE, the government customer needs to buy in to the new paradigm as well.	X	X		X	X

TABLE 10.—Concluded.

Citation	Observations	SA	SC	SAD	KDF	FMV
16	MBSE methods must cover the full system life cycle. Extending MBSE methods will require both methodological advances and development of supporting processes and tools.					X
16	The MBSE value proposition needs to be convincingly demonstrated on real-world problems. Specifically, the benefits of MBSE (e.g., elimination of rework, cycle-time reduction, risk reduction, and cost reduction) need to be shown to system acquisition managers, program managers, and SEs for large-scale projects covering different real-world systems of interest.	X			X	
16	SEs should begin to think of V&V of system models and quality of models in much the same way as software engineers have.					
16	Recent advances in complex systems engineering methodologies need to be incorporated within the MBSE rubric.		X		X	

TABLE 11.—FUTURE MODEL-BASED SYSTEMS ENGINEERING (MBSE) OBSERVATIONS: INDUSTRY
[Stakeholder analysis (SA). Strategic challenges (SC). Strategic advantages (SAD). Key driving forces (KDF). Future MBSE vision (FMV).]

Citation	Observations	SA	SC	SAD	KDF	FMV
2	A transformation program started in February 2019.					
2	We are redefining the future of model-based engineering (MBE), trying to evolve a path for MBSE as an enterprise-wide effort contributing mostly to our defense side.					X
2	An industry organization is working with Department of Defense (DOD) to help them with solutions and dealing with the transition to Dr. Griffin's vision at Office of the Secretary of Defense (OSD) and David Cohen's goals at Naval Air Systems Command (NAVAIR).				X	
2	We have already been using Systems Modeling Language (SysML) and engage more digital tapestry and integrated digital domain approaches and will continue to be more efficient.					X
2	The ability to make improvements in automating systems engineering is directly related to the value that companies place on systems engineering in the first place.				X	
2	It will take another decade to grow the need for a truly dedicated functional homeroom and managers to help capture it and develop systems engineers (SEs).	X	X			
2	There is a strong upward trend in the use of MBSE that is being driven by the largest aerospace companies, NAVAIR, and others.	X			X	
2	There is not as much of a trend at smaller companies, but they are getting driven towards it by their customers.					
2	Large and small companies are all looking for increased efficiency.	X	X		X	
2	It will take some time for us to have some evidence of the value of MBSE before it really takes off unless some forcing function comes along, which we are starting to see.				X	
2	I am involved with accelerating the deployment of MBSE across our company and minimizing the risk in doing it.		X			
2	We have seen an enormous increase in interest in systems modeling over the past 2 years.		X		X	
2	Companies are beginning to see good SEs as a competitive advantage in being able to unlock value.	X			X	
2	Has 20 years experience with MBE, and 7 years with SysML using Capella software.					
2	We are well over 70 percent model based in the early phases of a project. It is easier to support a model in the earlier phases.		X			

TABLE 11.—Concluded.

Citation	Observations	SA	SC	SAD	KDF	FMV
2	We are dipping into the shallow end of the pool for MBSE.					
2	We started hiring industrial engineers with systems engineering background 3 years ago. Our propulsion and thermal groups are using modeling. Our biggest tool designers are model based.	X				
2	However, we do not have a real requirement for MBSE with our systems complexity.		X		X	
2	I expect a far more collaborative environment up and down the supply chain.	X				X
2	One industry response for what works best with the way your organization currently engages systems engineering is enterprise-wide approaches for MBSE versus a project approach.					X
2	"Ten to fifteen percent now, but significant growth will occur, on the order of three to four times that over the next 3 years; We are preparing some big programs to use MBSE."		X			
2	One of the biggest adopters to date has 25 to 30 percent now but rapidly closing to 80 percent in the next 5 years in MBE.		X		X	
2	We are focused on reducing development cycle time from 10 to 12 years to less than 3 years through MBSE.		X		X	X
2	There is a worry about tools being selected that end up driving processes that are not conducive to doing good systems engineering.	X				
2	We are trying to work across our space programs to standardize use of MBSE.		X			X
2	Companies are beginning to see good systems engineering as a competitive advantage in being able to unlock value and allow people to see novel and more efficient ways to do things.	X	X		X	X
2	I am leading our corporate-wide functional leadership team while focusing on MBSE.	X				
2	Another key challenge in adopting MBSE is tools can be too inflexible especially as you marry tool sets together.					
2	Another key challenge in adopting MBSE are tool and model transition issues as not all tools work together.					X
2	Another key challenge area is dealing with standards, defining proper ontologies, and lack of model continuity all along the life cycle.					X
2	Another big challenge is the interface of MBSE with the customer.	X	X			
2	A key challenge with making systems engineering faster and more efficient is dealing with cultural issues and change.		X		X	
2	Key challenge #3 for MBSE is workforce training issues.	X				
2	A strong uptick occurring in systems engineering and MBSE and Digital Engineering Strategy is happening.		X		X	
2	Demonstrating evidence of value and real examples of return on investment appear to be the key barrier to growth for MBSE.				X	
2	It is extremely important that SEs be innovative at my company.		X			

TABLE 12.—FUTURE MODEL-BASED SYSTEMS ENGINEERING (MBSE) OBSERVATIONS: NASA
[Stakeholder analysis (SA). Strategic challenges (SC). Strategic advantages (SAD).
Key driving forces (KDF). Future MBSE vision (FMV).]

Citation	Observations	SA	SC	SAD	KDF	FMV
1	The goals of MBSE Infusion and Modernization Initiative (MIAMI) are to make systems engineering easier.					X
1	The digital revolution provides new solutions.			X	X	X
1	The digital revolution offers new capabilities.				X	X
1	The vision is this: NASA engineers enable extraordinary, unprecedented missions by adopting system-focused, human-centered, influential technologies for the benefit of all.	X			X	X
1	Envisioned a future automated mission design that is human centered and data driven.					X
1	Immersive, collaborative environments will enable rapid interaction in a distributed, seamless way.				X	X
1	Immersive, collaborative environments will enable deeper insight into mission design requirements and constraints.					X
1	An immersive environment simulates system of interest in operation.					X
1	Immersive, collaborative environments will enable distributed, seamless collaboration in a personal, mixed-reality work environment.					X
1	Digital personal assistants will help increase productivity.					X
1	The machine will know NASA guidelines and account for them in the design; the human will tailor guidelines as appropriate for each design.					X
1	Technical training will be more efficient and enjoyable through knowledge-sharing infrastructure and personalized interactions with the machine.					X
1	The machine will retain and provide the wisdom of the pioneers.					X
1	Development cycles will evolve to take advantage of that wisdom. There will be continuous data gathering and incremental learning.					X
1	Human-guided, machine-generated mission design is a projected far-term capability.					X
1	A software architecture that is flexible and independently deployable is a projected far-term capability.	X				
1	Software service and marketplace for automated verification and validation of software is a projected far-term capability.					X
1	Radical digital transformation is a projected far-term waypoint.				X	
1	Artificial intelligence (AI) tools for autonomous decisions are a projected far-term capability.					
1	AI tools for continuous learning are a projected far-term capability.					X
1	Automated data queries that provide knowledge when asked are a projected far-term capability.					X
1	Predictive analytics is a projected far-term capability. What will happen?					X
1	Science and innovation drive is a strength at NASA.			X	X	
1	Motivation to explore the unknown is a strength at NASA.			X	X	X
1	Exploration missions to distant planets are a strength at NASA.			X	X	X
1	World-class facilities are a strength at NASA.			X		
1	A very experienced workforce is a strength at NASA.	X		X		
1	Short-term funding cycles are a weakness.		X		X	
1	Rigid procedures that limit innovation are a weakness at NASA.		X			
1	The cost and schedule overruns on some major programs are weaknesses at NASA.		X			
1	The aging information technology (IT) infrastructure is a weakness at NASA.		X			
1	The comparatively low salaries are a weakness at NASA.		X		X	
1	The aging workforce is a weakness at NASA.		X			

TABLE 12.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
1	Commercial partnerships offer opportunities at NASA.	X		X		X
1	Digital transformation provides opportunities for NASA.			X	X	X
1	High-performance computing and space communications provide opportunities at NASA.			X		
1	Low-cost satellites (CubeSats and SmallSats) provide opportunities at NASA.			X		
1	Competition in hiring and retaining science, technology, engineering, and mathematics (STEM) employees is a potential threat to NASA.		X		X	
1	The deprioritization of the basic science research pipeline is a potential threat to NASA.		X			
1	A potential threat to NASA is a change in national priorities.		X		X	
1	The waning of public interest is a potential threat to NASA.		X			
3	MBSE plays a critical role in the radical transformation of NASA, especially as you increase the number of missions ×10, ×100, ×1,000(+) and eliminate most nontouch overhead positions.				X	
3	A metric we should track is what percentage of resources does the agency spend in MBSE-related activities versus all others. The amount now may be somewhere between 10 to 30 percent. In 20 years, expect that to be somewhere between 70 to 90 percent.					
3	Running digital transformation to its logical conclusion is not an easy task, not only physically and resource wise, but even conceptually.		X		X	
3	How broad is the MBSE community in 20 years? Assume model-based across engineering, so MBSE is not separated any more than systems engineering is separated out from other disciplines.	X				X
3	How broad is the MBSE community in 20 years? Can we talk about what we might not see coming? We want to make leaps rather than extrapolating linearly.					
3	How broad is the MBSE community in 20 years? It will be integrated through to management and human resources and connected through engineering.	X				X
3	What are people doing with MBSE? They are meeting more special needs, getting information we need from where we need it, but definitely not using a single tool for everything.					X
3	What are our new ways of working? There are many tools, but choosing by preference and features, you do not have to worry about if they will interface because, of course, they will.					
3	What are our new ways of working? There is a menu for how to initiate systems engineering; there are tools developed and available that can optimize it.					
3	What are our new ways of working? One can see the beginning of what we have now and assume it will be mature or can assume a disruption will happen that changes how we work.				X	
3	What are our new ways of working? There is component-based systems engineering that is highly reusable and open source with components, frameworks, and models designed by composition, instead of decomposition.					X
3	What are our new ways of working? A breakthrough in software is that we can use Application Programming Interfaces (APIs) and wrappers to make use of predefined modules for each capability.	X				
3	What are our new ways of working? There are visualizations to pull up data processes and information in more understandable ways, like how Excel® (Microsoft®) transformed data visualization.					X
3	What are our new ways of working? We use haptics and auditory cues.					

TABLE 12.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
3	What are our new ways of working? It can give information about a concept of operations (conops) and functional architecture.					X
3	What are our new ways of working? There is more intelligence to offer ideas for tradeoffs and design options.					X
3	What are our new ways of working? Help to filter data and options will be very helpful and necessary.					X
3	What are our new ways of working? MBSE was inspired by MB Software Engineering where the future of software engineering could be "machine programming." Systems engineers (SEs) can specify conops and machine system engineering builds optimized designs.					X
3	How might you want to get there? Meet in the middle.					
3	How might you want to get there? Directing from top does not work without the individual will to do it.	X	X			
3	How might you want to get there? Focus on making connections and seeing and sharing those in systems easier is needed.					X
3	How might you want to get there? We need just the right amount of structure with some agility in the roadmap to help.		X			
3	How might you want to get there? Strategic group should set expectations, avoid tools, etc. (e.g., anyone can work anywhere, anyone can use any tool, data seamlessly linked, etc.).					X
3	How might you want to get there? System design and MBSE added to core, basic engineering curriculum.				X	
3	How might you want to get there? System modeling and Systems Modeling Language (SysML) (or its advanced derivatives) included as an engineering methodology in addition to the usual mathematical and analytical modeling.					
3	There is a need to be more natural and discipline rich in our work.					X
3	Better visualizations are needed.					X
3	Discussion theme: agile versus structured approach to MBSE development, after breakthroughs we get several solutions, then filter into best practices until next disruption.					
3	There should not be an “MBSE community” in 20 years.					X
3	Much like the use of computer-aided design (CAD) in design no longer needs advocates, we should be aiming at normalizing MBSE to the point it is the default way of executing a project.					X
3	MBSE is absorbed as a routine and common practice in future engineering activity.	X				X
3	MBSE evolves to include within itself the ability to expose and explain a systems model's functions and behavior to nontechnical readers.					
3	Any spacecraft or system (especially any involving humans) will routinely embed or contain within itself its own maintenance and repair manual that includes its system model along with other functional, assembly and component schematics, independent verification and validation (IV&V) test results, etc. The embedded maintenance and repair manual is expected to include tools and software (e.g., SysML) to render and explore the models contained within.					X
3	How might you want to get there? Today's model-based SEs do not know they are model-based SEs. They think they are SEs who just happen to use modern thinking and tooling.	X				X
17	An action is to assess and recommend a MBSE approach for use across NASA and NASA tool standardization for model sharing and use of MBSE tools on projects.	X				X

TABLE 12.—Concluded.

Citation	Observations	SA	SC	SAD	KDF	FMV
17	A focus area to improve systems engineering: MBSE use across NASA can make system engineering easier by allowing computers to do what computers are good at so people can focus on what people are good at doing.	X				X
17	A focus area to improve systems engineering: MBSE workforce approach across NASA and NASA tool standardization for model sharing.	X				X
17	A longer term (5 to 20 years) outcome of systems engineering improvement is more intense systems-based perspective and understanding throughout the agency.					X
17	A longer term (5 to 20 years) outcome of systems engineering improvement is system modeling tools that integrate with manufacturing and software development.	X				X
17	A longer term (5 to 20 years) outcome of systems engineering improvement is adapting to emerging capabilities and technology.				X	X
17	A longer term (5 to 20 years) outcome of systems engineering improvement is reusable requirements and test procedures.					X
17	A longer term (5 to 20 years) outcome of systems engineering improvement is a more integrated, progressive, efficient, and capable agency.	X			X	X
17	A longer term (5 to 20 years) benefit of systems engineering improvement is improved integration across complex projects involving multiple centers and partners.	X	X	X	X	X
17	A longer term (5 to 20 years) benefit of systems engineering improvement is complex system of systems modeling and increased integration between hardware and software.		X	X	X	X
17	A longer term (5 to 20 years) benefit of systems engineering improvement is the ability to support the integration of complex program information and data architectures.		X		X	X
17	A longer term (5 to 20 years) benefit of systems engineering improvement is consistency across the NASA systems engineering workforce.					
17	A longer term (5 to 20 years) benefit of systems engineering improvement is to take advantage of statistical engineering, advanced modeling, and physics-based capabilities.	X			X	X
17	A longer term (5 to 20 years) benefit of systems engineering improvement is more effective design solutions and risk awareness.					X
17	A longer term (5 to 20 years) benefit of systems engineering improvement is to reduce development time and cost.		X			X
17	A longer term (5 to 20 years) implementation is a fully integrated systems data architecture via model-based engineering (MBE).				X	X
17	A longer term (5 to 20 years) implementation is a design baseline (T, t, $) maintained across product life cycle.					
17	A longer term (5 to 20 years) implementation is a design baseline to systems simulation.					X
17	A longer term (5 to 20 years) implementation is a more robust systems engineering analysis capability.					X
17	A longer term (5 to 20 years) implementation is a richer more graphical evaluation capability.					X
17	A longer term (5 to 20 years) implementation is digital twins of operational components (hardware and software).					X
17	A longer term (5 to 20 years) implementation is a design baseline to advanced manufacturing capability.					

TABLE 13.—FUTURE MODEL-BASED SYSTEMS ENGINEERING (MBSE) OBSERVATIONS: OTHER GOVERNMENT AGENCIES
[Stakeholder analysis (SA). Strategic challenges (SC). Strategic advantages (SAD). Key driving forces (KDF). Future MBSE vision (FMV).]

Citation	Observations	SA	SC	SAD	KDF	FMV
2	"We just developed our Digital Engineering transformation strategy. We took the Department of Defense (DOD) strategy and asked—What does that mean to our organization, and what do we need to do the next 3, 5, and 10 years?"				X	
2	Led effort in establishing the DOD-led national Institutes for Manufacturing Innovation (IMIs) such as the Digital Manufacturing and Design Innovation (DMDI) Institute.					
2	Our digital engineering strategy originated out of my office.				X	
2	I developed an open concurrent design software as a multidisciplinary tool that uses a lot of Systems Modeling Language (SysML) and design constructs involving 20 to 25 disciplines from early conceptual design used to support the concurrent design process.	X				X
2	I have been heading up our effort to start using model-based engineering (MBE) approaches starting 7 years ago.					
2	MBSE has been fully embraced by our leadership.	X	X			
2	We jumped into our systems engineering transformation initiative in 2014. We are now 5 years into it, and it is expected that we will complete the majority of the work over the next couple of years.					
2	Heads up a 1-year-old department involved with nuclear weapons component development to better focus systems engineering and grow use of MBSE SysML modeling.					
2	We are 15 to 20 percent MBSE after 10 months, but we should be >50 percent in 2 to 3 years from now.					
2	Until we change acquisition policies that allow for use of digital artifacts, I am not sure we will get much further than 40 to 50 percent of our systems engineering doing MBE.		X		X	
2	I am disappointed that different SysML tools do not better work together.					
2	A key challenge with making systems engineering faster and more efficient is dealing with cultural issues and change.		X		X	
2	The basics of systems engineering people leadership skills (PLS) and systems thinking are not overtly being emphasized at the DOD with no training.		X			
2	There is greater recognition of the need and increased emphasis for strong PLS. It is mostly something that is innate to start with and people with strong PLS have to be hired.		X			
2	Innovation is fundamental to systems engineering; systems engineers do tradeoffs and look at alternative ways of doing things.			X		X
4	We must modernize our defense systems and prioritize speed of delivery to be able to fight and win the wars of the future.				X	
4	These comprehensive engineering environments will allow DOD and its industry partners to evolve designs at the conceptual phase, reducing the need for expensive mockups, premature design lock, and physical testing.	X				X
4	The (DOD) goals promote the use of digital representations of systems and components and the use of digital artifacts as a technical means of communication.				X	X
4	Through increased computing speed, storage capacity, and processing capabilities, digital engineering has empowered a paradigm shift from the traditional design-build-test methodology to a model-analyze-build methodology.					X

TABLE 13.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
4	This shift extends beyond the engineering community with an impact on the research, requirements, acquisition, test, cost, sustainment, and intelligence communities.	X	X			
4	The digital engineering transformation offers similar positive changes for business operations including acquisition practices, legal requirements, and contracted activities.	X	X			X
4	DOD defines digital engineering as an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support life-cycle activities from concept through disposal.				X	X
4	The DOD Goal 1 is to formalize the development, integration, and use of models to inform enterprise and program decision making.					X
4	The DOD Goal 2 is to provide an enduring, authoritative source of truth.					X
4	The DOD Goal 3 is to incorporate technological innovation to improve the engineering practice.		X		X	X
4	The DOD Goal 4 is to establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders.					X
4	The DOD Goal 5 is to transform the culture and workforce to adopt and support digital engineering across the life cycle.	X			X	X
15	A challenge that organizations may encounter when infusing digital model-based engineering (DMbE) is assessing the value added to the organization (Challenge 1).	X			X	
15	Overcoming organizational and cultural hurdles will be a challenge including resistance to adoption and barriers to adoption and implementation (Challenge 2).		X		X	
15	A challenge that organizations may encounter when infusing DMbE is adopting contractual policies and technical data management (Challenge 3).		X			
15	A challenge that organizations may encounter when infusing DMbE is redefining configuration management. The DMbE environment changes the range of configuration information to be managed to include performance and design models, database objects, as well as more traditional book-form objects and formats (Challenge 4).					X
15	A challenge that organizations may encounter when infusing DMbE is developing an information technology (IT) infrastructure that is flexible, reconfigurable, and updatable (Challenge 5).					X
15	A challenge that organizations may encounter when infusing DMbE is ensuring security of the "single source" of truth (Challenge 6).		X			
15	A challenge that organizations may encounter when infusing DMbE is the potential overreliance on quantitative data over qualitative data; properly assess the quantitative results to give them the appropriate weight in subsequent decision making (Challenge 7).					
15	The Task team developed a recommendation to conduct a study to understand how contractual language influences current acquisition and engineering processes with regard to the exchange of electronic data and models among various types of organizations (e.g., government-government boundary and government-industry boundary) and what kind of impact DMbE would have on the relationships is needed. The results from the study should also identify what configuration items need to be addressed in the contractual language (Recommendation 1).	X	X			
15	The Task team developed a recommendation to identify best practices and framework necessary to convey the technical accuracy, precision, and uncertainty of data and information sufficient for subsequent, unambiguous, interpretation and use (Recommendation 2).					X

TABLE 13.—Continued.

Citation	Observations	SA	SC	SAD	KDF	FMV
15	The Task team developed a recommendation to identify metrics that highlight how an organization can qualify and quantify its return on investment in DMbE, which will vary based on project or program (Recommendation 3).				X	
15	The Task team developed a recommendation to develop a well-defined process to identify when and where to employ DMbE (ensure tailorability). Rather than attempt a complete shift, consider staging the transition. Identify a common activity or process and make a determination of how that activity would occur with digital artifacts rather than written ones. When feasible, incorporate existing processes that already use digital artifacts (Recommendation 4).		X			
15	The Task team developed a recommendation to establish a follow-on task team to identify forums for implementers and users of DMbE to identify and share best practices, gaps, and tools for cross-platform and cross-agency use and build or update a calendar to maintain situational awareness (Recommendation 5).	X				
15	One expectation an organization might have regarding the potential benefit or result of incorporating DMbE is informed decision making through increased transparency and greater insight (Expectation 1).					X
15	One expectation an organization might have regarding the potential benefit or result of incorporating DMbE is enhanced communication (Expectation 2).					X
15	One expectation an organization might have regarding the potential benefit or result of incorporating DMbE is increased understanding for greater flexibility and adaptability in design (Expectation 3).					X
15	One expectation an organization might have regarding the potential benefit or result of incorporating DMbE is increased confidence that the capability will perform as expected (Expectation 4).					X
15	One expectation an organization might have regarding the potential benefit or result of incorporating DMbE is increased efficiency (Expectation 5).					X
15	Prerequisites for the infusion of DMbE include management support and advocacy, technical capability readiness, and organizational and cultural willingness (or lack of resistance) to adopt a new methodology.	X	X		X	
15	DMbE is the use of digital artifacts, digital environments, and digital tools in the performance of engineering functions.					X
15	DMbE is intended to enable practitioners to engineer capabilities using digital practices and artifacts in a collaborative environment, creating a digitally integrated approach with a federated single source of truth.				X	X
15	Disrupting the current practices with different methods could appear to put the success at meeting or exceeding expectations at risk, with potentially negative consequences for the taxpayer, system user, and recipient of the engineered item.	X	X			
15	At the NASA Jet Propulsion Laboratory symposium, a conversation ensued from Dr. Miller’s presentation regarding how to aid in the adoption of MBSE across Federal organizations with varying missions. It was evident from this discussion that leadership expectations were largely unknown.	X	X			

TABLE 13.—Concluded.

Citation	Observations	SA	SC	SAD	KDF	FMV
15	In 2014, at the Jet Propulsion Laboratory's (JPL) MBSE Symposium, NASA's Chief Technologist Dr. David Miller briefed his view of model-based infusion with "MBSE: Harnessing Technology to Revolutionize NASA's Engineering Practice." Dr. Miller presented his perspective on the interactions among science, technology, and engineering disciplines (Figure 1). Many members of the audience viewed this briefing as the first written indication from a senior leader within a Federal agency regarding what leadership would expect from a wholesale shift to the method of model-centricity in systems engineering (Figure 2); e.g., what problems it might solve, what improvements it might make, and what advancements might be possible.	X	X	X		

TABLE 14.—FUTURE MODEL-BASED SYSTEMS ENGINEERING (MBSE) OBSERVATIONS: PROFESSIONAL SOCIETIES

[Stakeholder analysis (SA). Strategic challenges (SC). Strategic advantages (SAD). Key driving forces (KDF). Future MBSE vision (FMV).]

Citation	Observations	SA	SC	SAD	KDF	FMV
5	Future of systems engineering (FuSE) is focused on transforming systems engineering to realize a vision that stretches beyond the current boundaries of systems engineering to address the complexity and nondeterministic nature of tomorrow's problems.		X		X	X
5	A 10-year major development effort is needed for responding to disruptive technologies and complexities that challenge the status quo.	X	X		X	
5	One of the biggest common systems engineering challenges is the impact of advanced technologies such as autonomy, artificial intelligence, and augmented reality.				X	X
5	One of the biggest common systems engineering challenges is the increase in nondeterministic, quickly changing environments with high levels of uncertainty.				X	X
5	One of the biggest common systems engineering challenges is the greater levels of vulnerabilities from interconnectedness.				X	
5	One of the biggest systems engineering challenges is finding systems engineering leaders without a poor knowledge of management and leveraging of resources and a good understanding of investments across the life cycle of a project and across projects.	X	X			
5	Two of the biggest systems engineering challenges are finding partners with a fast rate of adaptation and adoption of technology advances and that business, mission, and operations complexity is growing faster than our ability to manage it.		X		X	X
7	Artificial intelligence (AI) is leading systems engineering into this next evolutionary state (of systems engineering processes and models).					
7	MBSE will be a set of models used to understand different aspects of the system.					X
7	Agent-based models provide a modeling approach to study the sociological influences within an organization and culture directly. This provides insight into how the public may respond to new services or capabilities and how social interactions may help or hurt the flow of information within the organizations.					X
7	The next level of systems requires an evolution of systems engineering processes and models.					
7	System models open the door for systems engineers (SEs) to provide design guidance, not on the engineering of components, but on the engineering of the system, allowing a balance of system component functions to achieve a best balance of system performance.	X				X

TABLE 14.—Concluded.

Citation	Observations	SA	SC	SAD	KDF	FMV
7	System models will provide the transfer medium to collect and maintain knowledge of the system and its performance.					X
7	As system models advance, we will need new methods, which will lead to the definition of new practices.					
7	This system-modeling basis is necessary for the next evolutionary step toward more complex artificial intelligence (AI) systems.		X			
7	AI is leading systems engineering into this next evolutionary state (of systems engineering processes and models).					
7	Organizational system models can show the sociological influences on the flow of development and operations within the organizational structures.					
7	Organizational system models show how the system interacts with sociological forces in application, providing some early understanding of emergent behavior and possibly some unintended consequences.					X
7	Systems value models will aid validation and provide the capability to directly compare the preferences of stakeholders to the system characteristics through the development life-cycle phases.					
7	SEs need to employ tools (system models) that enable design and development at the system level.					X
7	Systems engineering transformation will evolve more quickly with the definition of the set of system models needed to properly understand a specific system.					
8	System value models appear to provide a mathematical basis to define and guide the system development with the stakeholder's expectations.					
8	Mathematical category theory provides the mathematical definition of a system. Category theory provides the mathematical structure to identify the system theoretical aspects from the physical, logical, and social functions and interrelationships of the system.					X
10	Agility and resilience are measured not only by the system's ability to endure and adapt in context but also the ability of the engineering enterprise, and all of its life-cycle management activities, to rapidly respond with verified and validated solutions.		X		X	X
10	MBSE is the core business capability to digitally transform for advantage.				X	X
10	Multidisciplinary in nature, systems engineering spans over traditional boundaries providing an integrative view of the essential concepts required to innovate.	X	X	X		X
12	Systems engineering will have to invest a lot of effort in the coming years to overcome the many hurdles towards seamless interactions across the life cycle.					X
12	A big challenge for the future is to better align MBSE and product lifecycle management (PLM) initiatives.					X
12	An aligned combination of MBSE and PLM capabilities could become the backbone for enabling such (digital) enterprises in the future since they combine essential properties needed for a structured digital transition.			X	X	X
12	For this digital transition to happen, it needs a strong and corporate commitment with foresight, software competencies beyond those on board for normal day-to-day work, and lots of attention to the development of the digital user community.	X	X		X	
12	The lack of comprehensive, seamless, commercially available MBSE tools has been noted all along as a big handicap for the advancement of MBSE.					X

TABLE 15.—FUTURE MODEL-BASED SYSTEMS ENGINEERING (MBSE) OBSERVATIONS: SOFTWARE VENDORS
[Stakeholder analysis (SA). Strategic challenges (SC). Strategic advantages (SAD). Key driving forces (KDF). Future MBSE vision (FMV).]

Citation	Observations	SA	SC	SAD	KDF	FMV
2	There are 7,000 tool customers.	X				
2	I am responsible for adopting MBSE in the United States using Systems Modeling Language (SysML) and building awareness and promoting its advantages.	X				
2	No Magic (Dassault Systemes) kicked off its new academic program initiative.	X				
2	We are the bridge between MBSE and engineering analysis.	X				X
2	Vendor is working the digital factory and how to digitalize product development process.	X				X
2	We are “by systems engineers (SEs) for SEs,” not software people, but systems people.	X				
2	Siemens and IBM are looking at replacing SysML and are pushing digital twin.	X				X
2	A key challenge with making systems engineering faster and more efficient is dealing with cultural issues and change.		X		X	

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