Realized Benefits from the Model-Based Systems Engineering Infusion and Modernization Initiative

By Jessica R. KNIZHNIK,[1)] Karen J. WEILAND,[2)] Trevor A. GRONDIN,[3)] Kelley M. JONES-MCDOWALL,[4)] and Jon B. HOLLADAY[5)]

[1)]*Goddard Space Flight Center, NASA, Greenbelt, USA*
[2)]*Glenn Research Center, NASA, Cleveland, USA*
[3)]*Langley Research Center, NASA, Hampton, USA*
[4)]*Kennedy Space Center, NASA, Merritt Island, USA*
[5)]*NASA Engineering and Safety Center, Hampton, USA*

Although Model-Based Systems Engineering (MBSE) as a concept has existed for over a decade, overall acceptance within the National Aeronautics and Space Administration (NASA) has been slow and is now growing. Since 2016, NASA's MBSE Infusion And Modernization Initiative (MIAMI) has proven MBSE's value to and increased its adoption at NASA. MBSE Pathfinder projects provided focused use cases that demonstrated both qualitative and quantitative benefits for systems engineering activities, and demonstrated the ability to connect MBSE models with discipline models such as structural loads and safety and mission assurance. MIAMI assisted NASA's field centers to establish or enhance an MBSE presence. MIAMI partners with JAXA's Systems Technology Unit to share lessons learned and demonstrate how MBSE can be used across organizations. Following its successful test cases, MIAMI is using design thinking, lean startup, and high technology marketing methodologies to implement a targeted deployment of its Community of Practice and other resources.

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1. Introduction

Though model-based engineering approaches such as Model-Based Systems Engineering (MBSE) existed since the late 1980s and early 1990s,[1)] the United States National Aeronautics and Space Administration (NASA) did not adopt them at their inception. As the international systems engineering (SE) community created guides for implementing MBSE and the International Council on Systems Engineering (INCOSE) included MBSE in its visions for 2020 and 2025, the NASA systems engineering community took notice. They began investigating MBSE's utility for, and applicability to, NASA's missions in earnest in 2016 with its MBSE Pathfinder effort. Since that time, the MBSE Pathfinder grew into NASA's MBSE Infusion And Modernization Initiative (MIAMI), which now encompasses the MBSE Pathfinder, a MBSE Community of Practice, a Strategy Group, and an Advisory Board. Its partnerships with internal NASA programs, projects, and organizations as well as with external collaborators such as the United States Department of Defense (DoD) and the Japan Aerospace Exploration Agency (JAXA) allow MIAMI to overcome technical and cultural barriers to infuse MBSE within NASA operations.

2. Background and Prior work

As early as 2009 NASA began exploring model-based approaches through an agency-level systems engineering working group and began its NASA Integrated Model-centric Architecture (NIMA) initiative in 2011.[2)] Both groups investigated MBSE's potential, spread MBSE concepts throughout the NASA field centers, and laid the foundation for interest in further MBSE investigation and implementation.

3. Engagement with Working NASA Engineers

3.1. MBSE Pathfinder

During the fall of 2015 the NASA Engineering and Safety Center (NESC) began its own NASA wide MBSE investigation. Since then, a group of roughly two-dozen part-time volunteers from across every NASA Center formed teams to tackle focused complex NASA analogs across the entire life-cycle, sometimes called Systems Engineering Vee. Teams demonstrated that the MBSE learning curve was not that harsh, while others organically migrated to and developed a hybrid agile software development approach. Still others demonstrated that early career SE leaders can be just as effective as experienced ones, and that all SEs can pick up modelling skills quite easily. In the end, close to a dozen use cases demonstrated the value and ease of MBSE on NASA applications. Later, MIAMI was developed, whose job it was to continue expansion of MBSE by developing a recognized core capability of modelers within the agency and advance model-based systems engineering at the agency.

Four years later over 150 people had been directly involved in the MBSE efforts. Some NASA branches (a grouping of roughly 30 people) now require their members to be trained in MBSE. Programs and projects continuously pop up that are using MBSE in some area or another, some full bore, other focused. MIAMI continued to build toward a recognized Community of Practice (CoP) which now acts as a focal point for engineers to use for getting started with MBSE and access a warehouse of MBSE lessons learned. Roughly a dozen programs and projects have been supported to varying degrees as they attempted to implement MBSE. NASA has analyzed and developed alignment plans for both industry and tool vendors. Similar efforts have focused on identification of future workforce, including academia, preferred curricula, training, etc.

Much of the work performed by the MBSE Pathfinder and MIAMI is also being utilized to inform larger NASA efforts, such as Digital Transformation of the Agency!

3.1.1. Test Cases

The first year of the MBSE Pathfinder focused on applying MBSE to a representative sample of NASA missions including, "1) mission architecture use and reuse for a humans-to-Mars campaign of missions; 2) additive manufacturing for rocket engine development, 3) mission element design of a Mars lander, and 4) mission flow shadowing of a sounding rocket project."[3]

This first iteration of the MBSE Pathfinder proved that NASA engineers could successfully learn and apply MBSE to NASA use cases. The MBSE Pathfinder expanded in its second year to using MBSE to perform engineering analysis on another representative sample of NASA missions including Humans-to-Mars In-Situ Resource Utilization (ISRU) architecture, architecture for a cis-lunar habitat, requirement verification for a rocket engine, early lifecycle mission flow shadowing for a sounding rocket, integrated ISRU and habitat architecture analysis and trade studies, and design trades for a launch vehicle payload adapter.[4,5] This second year also included a Cross Cutting Themes (CCT) team to address items common across the other subject areas.[6] This CCT team became the foundation for the NASA MBSE Community of Practice (CoP).

From there, the MBSE Pathfinder moved on to applying MBSE on active NASA missions. This third MBSE Pathfinder iteration fell into two categories: Cross Lifecycle Modeling (CLM)[6,7] and Active Project Partnerships (APPs).[6,8] The CLM work allowed MIAMI to investigate how MBSE decisions made early in a project's lifecycle would affect MBSE usability and utility later in that project's lifecycle. The APP work allowed MIAMI to explore MBSE under realistic programmatic resource constraints while also introducing MBSE concepts to non-MIAMI participants and seeding interest in MBSE on these active projects.

3.1.2. Cross Lifecycle Modeling

The Cross Lifecycle Modeling (CLM) team started in 2016 to pilot MBSE throughout the lifecycle through the NASA Sounding Rocket Program (SRPO), which is a program that is frequently going through all phases of the project lifecycle.

- Pre-phase A: Experiment design formulation
- Phase A: Experiment System Requirements Review
- Phase B: Experiment Preliminary Design Review
- Phase C: Experiment Critical Design Review/ Initial vehicle selection
- Phase D: Final vehicle selection/System level testing/ Integration to launch vehicle/Launch
- Phase E: Mission operations
- Phase F-Return to site/Disposal

The team has demonstrated proof of concept using a system modeling tool.[6,7] This will be wrapped up at the end of this year and will be shared with the MBSE CoP as an example and potential template for future projects and programs.

3.1.3. Active Project Partnerships

The MBSE Pathfinder began 2018 with 12 APPs: Exploration Medical Capability Systems Engineering and Integration[8], the X-Ray Imaging and Spectroscopy Mission Resolve instrument, Europa Independent Verification and Validation, a Model Based Safety and Mission Assurance Initiative, Deep Space Gateway and Transport (DSG&T) Systems Engineering and Integration, DSG&T Exploration Life Support Systems, Space Communications and Navigation Network Architecture through MBSE, Wallops Operations Surveillance System/SureTrak In Government, Resource Prospector, Stratospheric Aerosol and Gas Experiment IV Pathfinder Instrument Incubator Program, Computer Aided Systems Engineering Software, and Space Launch System Exploration Mission-2 Exploration Upper Stage Umbilical Design. In 2019, due to interest and availability, the first seven APPs continued their partnership with MIAMI. Each APP team created and executed its own modeling goals in line with its project's needs.

MIAMI provided MBSE resources to these APP teams as the APP team requested them and the resources became available. From this, MIAMI learned which resources would be valuable to continue to provide to NASA missions and engineers interested in using MBSE methods in their work. One such need included a CoP for MBSE users to work on common MBSE needs together.

3.2. MBSE Community of Practice

More than just building tools to implement a new technique of performing work, it takes people banding together to build best practices, share lessons learned, and demonstrate the benefit of the change. Along with establishing an institution that the community can lean on as they learn the new technique, MIAMI's CoP utilizes the NASA Engineering Network site to share best practices, capture lessons learned, connection to experts, and templates. The CoP also holds weekly meetings open to the whole agency to discuss specific topics that affect the whole MBSE community.

This CoP also serves as a hub for each of the ten NASA field centers' CoPs. Because MIAMI now has multiple prior and current participants at each of its field centers, these participants have carried what they learned with MIAMI to other non-MIAMI participants at their home centers. These groups now make up the CoPs at the field centers. They allow MIAMI to directly connect with MBSE users in person.

4. MIAMI Partnerships

MBSE at NASA has benefitted from the partnerships MIAMI forged internal and external to NASA. Within NASA, along with the APPs, MIAMI partners with the NASA Office of Safety and Mission Assurance (OSMA) on its Model Based Mission Assurance (MBMA) initiative.[9,10] This has allowed MIAMI to fold Safety and Mission Assurance (SMA) considerations into its models from their inception. The 2017 MBSE Pathfinder (including the teams focused on early lifecycle mission flow shadowing for a sounding rocket and integrated ISRU and habitat architecture analysis and trade studies), the 2018/2019 CLM team,[7] and a few of the 2018/2019 APPs integrated safety and risk analysis directly into their models.

MIAMI partners with groups implementing cloud infrastructure at NASA. These groups allow MBSE users to share licenses and collaborate on models across geographic locations. These efforts initially began with internal NASA collaboration and expanded to include collaboration with external partners, beginning with JAXA's Systems Technology Unit (STU).

In addition to MIAMI and STU's partnership on a shared space for model collaboration, MIAMI and STU have partnered with each other to share MBSE lessons learned in their respective organizations, focusing in on NASA and JAXA's shared interest in the Resolve instrument for the XRISM mission. MIAMI has also gained perspective on MBSE methodology creation.

MIAMI also maintains an external partnership with the US Department of Defense (DoD). In exchange for practical experience, lessons learned, and input into its Digital Engineering Strategy, the US DoD provided MIAMI with personnel for its Sounding Rocket work in the 2016 and 2017 MBSE Pathfinders as well as connections with other MBSE work occurring at NASA and US DoD's shared aerospace and defense contractors.

These partnerships combined began to showcase how MBSE can grow into Model Based Engineering (MBE), which has now made MBSE a key part of NASA's Digital Transformation initiative. MIAMI plans to leverage its greater agency visibility to support MBSE infusion.

5. Future MBSE at NASA

Because MIAMI has operated since 2016, it has experience with applying foundational MBSE to a representative sample of NASA missions and use cases. MIAMI will now build on that experience and deploy its knowledge and resources to NASA programs and projects using MBSE as their primary SE methodology. MIAMI will use 2020 to transition away from MBSE trials towards a focus on supporting implementation and evolving MBSE beyond the current state of the discipline.

5.1. Targeted Deployment of MIAMI Resources

A crucial tactical step for the MIAMI team was to select an appropriate project to drive the MBSE technique across the chasm from early adopters to early majority.[11]

The most logical group of engineers to approach to add MBSE as a technique to complete a project, launch/operate a mission, or enhance a capability are in most cases the Lead Systems Engineers (LSEs). The LSEs are typically the integrators of the project and those who have the responsibility for the overall technical competency of the project, mission, or capability. They are the ones pulling in all the different subsystems and disciplines together and have a basic understanding of the entire system. As long as the LSE is providing other key project stakeholders (such as project managers, program managers, chief engineers, other lead engineers, etc.) with the relevant information they need in an efficient and effective manner these stakeholders are typically not interested in the method the information was obtained. Thus, getting the LSEs on board with MBSE was crucial to getting the entire team to embrace it.

Based on assessing Moore's criteria[11], the MIAMI team identified five NASA projects approach to determine if they had interest in engaging with MIAMI. During 2020, the CoP and its cadre of modelers will support selected projects' top-level needs.

5.2. Long Term Strategy

Agency-level engineering leaders, SE leaders at the NASA Centers, and the MIAMI leadership team all recognized the importance of and need for top-level goals and objectives for future SE capability development. The future success of MBSE at NASA is tied both to its adoption by NASA engineers, programs, and projects, and to a long term strategy for SE. In addition, the MIAMI leadership team saw opportunities in the digital revolution for new approaches. To this end, they performed three activities as the first steps in the development of a long term strategy.

The first activity started when the MIAMI leadership team established a Strategy Group in June 2018 to look into the future of engineering at NASA from a SE perspective.[6] The Strategy Group was a small group of early to middle career employees with diverse experiences and technical backgrounds, and who were individually recognized for their innovation and new ideas. The members were from six different NASA field centers and represented the major mission areas of NASA. The members attended four face-to-face meetings and worked virtually otherwise. They used design thinking, interviews, clustering analysis, data visualization and synthesis, and more, to understand the current situation and formulate recommendations for the future. The deliverables from the Strategy Group were a vision, a roadmap, and a brief strategic plan that defined and planned a digital future for the next 20 years. The vision is a top-level statement and graphical depiction of the goals and objectives for SE modernization and will be used to communicate with the SE workforce and key stakeholders. The roadmap is a top-level table of technology-based capabilities over time. The strategic plan contains options and recommendations for approaches to accomplish the vision and roadmap. Additional details on the work processes, and the vision, roadmap, and strategic plan are in Ref. 12).

The second activity was a survey with external partners in industry, academia, engineering tool vendors, and other government agencies outside of NASA. The goals were to determine the current state of SE within their organizations; to understand their challenges and opportunities and future plans; and to obtain their opinions about the state and future of the SE discipline overall. NASA developed specific topics and questions of interest, and identified people at key external organizations to contact in order to meet these goals. Over 50 participants were interviewed, including technical leads, subject matter experts, systems engineers and practitioners, chief engineers, project managers, and middle and top-managers. The MIAMI leadership team is using the results to influence the future of NASA SE and MBSE, to evaluate and validate future plans, and to identify opportunities to lead, leverage the efforts of, or partner with, other organizations.

The third activity was a set of interviews and selected readings intended to understand the roles and responsibilities for long-term leadership of MBSE capability sustainment and advancement at NASA. The specific objectives were to learn what organizational structures and practices have been successful for culture change involving disruptive technologies, and to learn from past experiences of culture change at NASA. The MIAMI leadership team interviewed multiple people within NASA who participate in or lead culture change as leads and members of several engineering disciplines and human resources. They were middle career and later career, had varying levels of interest in new technology ranging from innovator and visionary to conservative. Each interviewee was invited to tell several stories about what did or did not work, and what they would keep or do differently as a way to solicit lessons learned. The interview results were unpacked and analyzed for options and recommendations. The MIAMI leadership team read several recent marketing and innovation books that offer perspectives on how to innovate and infuse ideas into practice.[11,13] The books were examined for best practices and examples of what works well for organizations similar to NASA and, conversely, how NASA might need to change.

The MIAMI leadership team intends to use the vision, roadmap, and strategic plan from the Strategy Group, the external survey results, their internal interview results, and findings from books to lead the formulation of a comprehensive SE strategy for NASA during the coming year. MBSE, model-based engineering, organizational structure, culture change, and partnerships and collaborations within and external to NASA will be major components of the strategy.

6. Conclusion

MIAMI has laid the foundation for successful MBSE implementation at NASA. Over the past four years it has aligned the MBSE capability across its field centers by testing MBSE on sample use cases, expanded to perform analysis, and prepared for using MBSE on active NASA missions with its CLM teams, APPs, and CoP. MIAMI is now prepared to focus on infusing MBSE implementation onto NASA missions and to carry its strategy forward to evolve MBSE beyond the current state of the discipline.

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