A Case Study on NASA MBSE Practices

Ryan Patton  
Missouri University of Science and Technology, Department of Engineering Management and Systems Engineering  
223 Engineering Management, 600 W. 14th St., Rolla, MO 65409-0370(673) 341-4572, rtpwx3@umsystem.edu

*Abstract*—System engineering evolves time and again to suit new methods for most cost-effectively and timely capturing the process involving architecture, concepts, requirements, etc… National Aeronautics and Space Administration (NASA), in keeping with the current trend across the aerospace industry to adopt Model Based Systems Engineering (MBSE) practices, has started grassroots efforts to determine how well it could fit into its different programs. By starting out implementing on a small-scale and across recently started programs, NASA can analyze on a broad front how MBSE principles at their core can best be incorporated with NASA while keeping with its current policies and processes.

Keywords—model based systems engineering, systems engineering, Pathfinder, FUELEAP

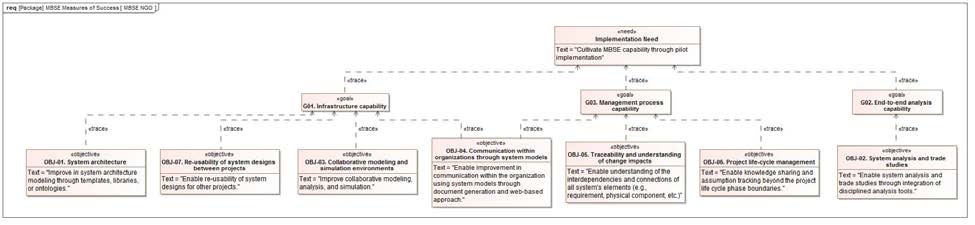
# Introduction

With many companies realizing the benefits of MBSE, especially within the aerospace industry as of late, NASA has started applying the approach to dominate its former document-centric approach. With a rich history in the United States of leading the charge for innovation and cultivating a culture of passionate learning in science, technology, engineering, and mathematics (STEM), NASA willingly studied different ways of implementing MBSE from 2011 through 2018. In 2016, the MBSE Pathfinder provided groundbreaking insight into adopting a digital approach to MBSE and over a two year lifecycle, systems engineering methods were implemented and covered across multiple phases to see how it fared with a real NASA spaceflight system [3]. Relatively few programs at NASA have openly accepted MBSE thus far due to their more flexible processes demanding less formal documentation. Recent efforts proving fruitful drive the inspiration for NASA to experiment with MBSE across some of their portfolio including the Fostering Ultra-Efficient, Low-Emitting Aviation Power (FUELEAP) project at NASA Langley Research Center (LaRC), the Pathfinder initiated by the NASA Engineering Safety Center (NESC) Systems Engineering (SE) Technical Discipline Team (TDT), NASA’s Space Communications and Navigation (SCaN) networks comprised of the Near Earth Network (NEN), the Space Network (SN), and the Deep Space Network (DSN), Space Launch System (SLS), Spartan, the International Space Station SERVIR Environmental Research and Visualization (ISERV) operations, Lunar Prospector-Discovery program, and James Webb Space Telescope (JWST) mirror testing [1, 4]. With bountiful programs in various stages of implementing MBSE practices, NASA will study its effects for continued outreach to other programs and eventually enterprise-wide if it proves to be universally cost-effective and time-saving.

The following sections will cover the implementation of MBSE within NASA programs to give a glimpse of what is in store for the future of NASA and the extent to which MBSE will most likely be implemented. Dealing with spaceflight systems and more academic applications of scientific exploration will not necessarily yield the same results as the rest of the more manufacturing-based, aircraft-focused defense industry. Due to the distinction and uniqueness in how NASA functions as an enterprise, the following program case studies aim to derive what benefits can be applied to the systems engineering processes already in place at NASA.

# MBSE Practices with FUELEAP

The FUELEAP program is a sub-program within NASA Aeronautics TACP, part of the agency ARMD, whose mission aims to cultivate new concepts and capabilities that can lead to innovative design concepts and breakthrough technologies that will transform the aviation industry. As a program, FUELEAP investigates the need for near-term widespread use of new airborne propulsion technologies that can offer compelling improvements in emissions, efficiency, and performance without requiring major industry investment in infrastructure, certification, or energy storage. MBSE analysis picked up when a heavy-fuel SOFC was chosen as a potential solution due to its on-board efficiency and its ability to leverage much of the existing industry infrastructure. The assessment as part of this analysis included: (1) safety-focused design and analysis of the integrated SOFC-powered aircraft; (2) development of a heavy-fuel hybrid-electric SOFC power system architecture; and (3) system and component testing for technology advancement including environmental and lifecycle economics impacts. In Fiscal Year 2017, the MBSE efforts implemented realized 4 main benefits covered in the sub-sections below [2]. The activities for a MBSE implementation plan can be seen below in Figure 1.



1. MBSE Objectives Implementation

## Clearer Identification of the Project Needs, Goals, and Observations (NGOs)

The activities developed using MBSE to identify NGOs included: (1) Creating templates, libraries, or taxonomy for system architecture; (2) Integrating to disciplined analysis tools; (3) Using concurrent modeling through MagicDraw Teamwork Server; (4) Using integrated tools for collaborative analysis; (5) Automating on-demand document generation capability; (6) Using a Web-based approach to facilitate communications; (7) Connecting traceability between various model elements; (8) Using models from Concept Requirement Review and beyond; (8) Demonstrating use of models to satisfy entrance and success criteria for gate reviews; and (9) Developing reusable templates, libraries, or taxonomy for use by other projects.

## Improved Communication Through the Use of Formal System Models

By using an existing TeamWork server, multiple users could access and modify a single SysML model simultaneously. Members could use MagicDraw to view the project SysML model without needing to worry about accidentally making unintended modifications and could also “lock” only sections they were currently updating. The visualization provided by the SysML diagrams helped visually represent the system to communicate project concepts to team members and shareholders. More relationships between system components were established, allowing for easier switches between demonstrating project information at higher levels and lower levels of detail. The team found a reduced need for separate figures to be developed across various software platforms due to SysMLs ability to define the system of interest and also to provide a drawing tool for project concepts. Ultimately because of this, time and money were saved for the parent organization.

## Better Preparation for Project Life-Cycle Reviews

The generation of multiple figures relevant to project management served as helpful tools and indicators for all project team members, not just the SE teams. By implementing updates across the whole project website, the information and status allowed for easy access and tracking by all team members and allowed for quicker updates with minimal effort. By posting key SysML diagrams to illustrate project status and upcoming tasks, team members could be notified when updated versions of project documents, drawings, and reports had been posted. This eased the confusion of members storing multiple copies of files for quick reference. During the third quarter of 2017, FUELEAP changed their life-cycle review to better reflect the work they had done as a direct result of their conceptual, project-level requirements. As a result, management received the progress status of the project well due to the outputs of the MBSE process during the planning and execution of the review. Follow-on efforts involve refining project requirements to a greater level of fidelity, further developing the FUELEAP SysML model to include updated requirements and re-generation of the project requirements document, and initial investigation into the creation of interfaces to other FUELEAP sub-team SysML models.

## Easier Identification of the Interdependencies Between Project Elements (i.e., The Relationship of Requirements to Physical Aircraft Subsystems, The Interfaces Between Subsystems, etc.)

By modelling key elements of the aircraft and the power system, the SE Team captured many of the most important characteristics in a graphic format. The graphic format proved useful as it contained logic and information to describe the interactions between systems. The SysML models allowed for new configurable, documented relationships unobtainable by conventional documentation standards.

# MBSE Practices with Pathfinder

A first of its kind, the NASA Engineering Safety Center (NESC) SE TDT initiated the MBSE Pathfinder effort in Fiscal Year 2016 with the goals and objectives to include developing and advancing MBSE capability across NASA, applying MBSE to real NASA issues, and capturing issues and opportunities surrounding MBSE. The Pathfinder team observed applied their existing and newly acquired system modeling knowledge and expertise to develop modeling products for a campaign (Program) of crew and cargo missions (Projects) to establish a human presence on Mars utilizing In-Situ Resource Utilization (ISRU). The team worked to develop a subset of modeling products required for a Program System Requirement Review (SRR)/System Design Review (SDR) and Project Mission Concept Review (MCR)/SRR. Over twenty lessons Learned and recommended next steps were identified in their discoveries. A summary of the goals, objectives, and lessons learned can be seen in the following sections [3].

## Goal 1: Demonstrate System Modeling for Mission Architecture Use and Resuse for a Human to Mars Campaign of Missions

The following objectives fulfill Goal 1 at the campaign and mission levels.

* Objective 1: Model Organization

Pathfinder’s project management could be partitioned in a separate and parallel space from the Mars Campaign modeling work due to the high-level structure. The Mars Campaign package contains elements related to multiple missions to accomplish a campaign and contain elements serving as patterns for individual missions. The package also modeled individual missions for the overall campaign. In addition, a Glossary package was created to provide definitions and explanations about the model elements to help the team understand the concepts included in the model. Along with the Glossary package was a Model Libraries package designed to organize information about the model would be reused. The creation of packages provided a method for handling system complexity and the modeling task.

* Objective 2: Parametric Analysis

The Extensive ISRU campaign and the first two cargo missions (initial cargo and recurring cargo) were modeled to fit into the general campaign and customized for the Extensive ISRU campaign. This was performed using Phoexnix ModelCenter (MC) plug-in for integration between SySML model and Matlab. The two nestd parametric analyses consisted of computing mass roll-up of each launch based on its payload’s content and then calling for discrete event simulation (DES) functions in Matlab. The benefits of parametric analyses include: (1) evaluating alternative campaign designs throughout the project life cycle; (2) determining the quantitative values of requirements during the earlier project life cycle; and/or (3) indentifying driver(s) of system’s performance requirements as part of resource planning and control process.

* Objective 3: Model Libraries

For Pathfinder’s effort to contain reusable elements in their libraries, two logical grupings of SysML elements with commonalities were identified and placed into Model Libraries package. It contains a hierarchial structuring of resources, their locations, and their associated technology areas. Several user-defined profiles used extended the SysML language and allowd the disciplined engineer or modeler to user “terms of the trade”. Different profiles were then set up for a Pathfinder team profile, a Lessons Learned profile, and a Campaign and NPR profile. The different profiles all contain relevant information able to be easily looked up and reused for other projects beyond Pathfinder.

## Goal 2: Mature the “Extensive ISRU” Campaign from the Architecture/Missions Design Analysis Toward a Program SRR by Producing Systems Engineering Products in a Model-Based Way

The only objective seen below fulfills Goal 2.

* Objective 5: Reviews

The team developed models that represent lifecycle review products capable of satisfying NASA lifecycle review entrance and success criteria at the Progam (Campaign) level and Project (Missions) level. The Program level used a System Requirements Review and System Definition Review. The Project level used a Mission Concept Review and System Definition Review.

## Goal 3: Understand, Demonstrate, and Apply Concepts of Model Re-Use

The only objective seen below fulfills Goal 3.

* Objective 7: Design Patterns

The Pathfinder team produced some recommended design patterns for future NASA missions/projects to consider applying to their models since SysML does not require a particular modeling approach or pattern. The team focused on design patterns found in Behavior, Structure, Requirements, and their relationships.

## Goal 4: Learn Configuration management and Collaboration Best Practices with Respect to Modelling and Assess Export Capabilities of Tools

The two objectives seen below fulfill Goal 4.

* Objective 3: Collaborative Modeling and Configuration Management

The team worked with MagicDraw with a model repository called Teamwork Server to serve as version control and updates. Multiple users could edit a piece at any given time. Commits needed to be tracked. The biggest difficult was following good “lock/unlock” etiquette and working with the Project Merge plugin. Each modelling session needed to be unlocked after every session to ensure others could edit. For the Project Merge plug in, with so many modelers working parallel merging each iteration meant a stop-work condition needed to be put in place everytime. In addition, the team benefitted by playing around with their own sandboxes and exploring the various capabilities.

* Objective 4: Model Export Capability

The team evaluated and used the Document Modeling plug in to generate a document directly from the model in MagicDraw. By utilizing this approach, team members didn’t need to learn scripting language but did require learning to model using viewpoints and views concept. The purpose is only to see the overall laborious setup of the chosen approach and would require an external document post-processing tool to give it a more professional look.

# MBSE Results

The FUELEAP SE Team noted modelling requirements in Systems Markup Language (SysML) can quickly become a cumbersome process, especially for large-scale project with many requirements to model and track. With hundreds or thousands of requirements on the board for spaceflight projects, modeling individual requirements can be so time-consuming and result in a model that is so large they may not be of any use to the project. For aeronautics research projects such as FUELEAP, capturing formal requirements and tracking them is at a much higher-level to where it makes sense to model the requirements.

The Pathfinder team noted three key lessons. Parametric Analaysis – Basic Analysis (e.g., simple mass roll-up) is possible within MagicDraw and its plugins available during the time of the effort. The team, to perform time-based simulation analysis (or other disciplined analysis), needed to use external tools to integrate advanced analysis with MagicDraw and was not part of the standard MagicDraw/MBSE Pathfinder toolset. For collaboration, the team used individual “sandbox” packages in the main model to experiment but this created validation errors due to multiple copies of model elements. Sandboxes as separate models would help the team incorporate changes into the main team model. As for terminology, the team encountered a lot of frustration and rework rehashing terminology as a result of each team member leveraging their own experience(s). The entire team was not on the same page regarding terminology, definitions, and over hierarchy.

Table 1, seen below, lists the Pathfinder team’s own observations from their systems engineering MBSE approach.

1. Accomplishments by Goals

| Accomplishments by Goals | | |
| --- | --- | --- |
| Goal | Goal Text | Accomplishments |
| 1 | Demonstrate system modeling for mission architecture use and reuse for a human to Mars campaign of missions. The system modeling would be done at the campaign and mission level | * The team demonstrated system modeling by developing numerous models for a Mars Campaign and Missions to take ISRU cargo to the Mars surface * Some of the developed models can be reused by other teams and are in a model library, as part of final deliverables. * The team acquired knowledge of, as well as developed some lessons learned and observations regarding model organization for a (Program) Campaign of Missions. * The team performed sensitivity analyses at the campaign level for two factors (mass limits for a particular launch, slips/delays in launch dates). |
| 2 | Mature the Extensive ISRU campaign from the architecture/mission design analysis toward a Progam SRR by producing systems engineering products in a model based way. | * The team developed 11 model based systems engineering products for the Extensive ISRU Mars Campaign. * The model based systems engineering products generated represent a subset of lifecycle review products for a Program SRR, Program SDR, Mission level CMR, and Mission level SRR. |
| 3 | Understand, demonstrate, and apply concepts of model reuse | * The team acquired knowledge of and, to some extent, applied model reuse as we developed our model based systems engineering products at the Campaign and Mission levels. * The team demonstrated model reuse by developing a model library that contains several reusable modeling assets. |
| 4 | Learn configuration management and collaboration best practices with respect to modeling and assess capabilities and tools. | * The team acquired knowledge of, as well as developed numerous lessons learned and observations regarding configuration management and collaborative modeling. * The team assessed the Document Modeling plugin and utilized it in the generation of the final report. |

# Conclusions

The FUELEAP team decided that modeling requirements in SysML may be worth it in projects only requiring high-level requirements and so it is critical early in the life cycle to decide the level of requirements needing to be modeled. Since FUELEAP was a first effort of its kind within NASA to implement MBSE principles like SysML to aeronautics, more efforts will need to be made to further cover the distinctions in how MBSE can be implemented differently in spaceflight systems compared to aeronautics systems within the enterprise. FUELEAP hopes to add on to existing models, including:

* System safety analysis, including FMEA and FTA, for the integrated SOFC power system
* Complete aircraft FHA
* Feasibility analysis of the integrated heavy fuel hybrid-electric SOFC power system as a transformational source of airborne power, using research-defined objective performance criteria as threshold values for feasibility.

The Pathfinder team leveraged MBSE principles for seven months and felt ready to identify the next steps which are currently under development. The next steps include: continuing to mature and advance the demonstrated parametric capability associated with performing trade analysis for a Mars Campaign; creating an Agency wide collaboration space for MBSE; developing common and reusable assets; further refining model governance principles; establishing a MBSE “boot camp”; and ascertaining the concepts of model Verification and Validation.

The efforts applied by both the FUELEAP team and Pathfinder team show the hesitancy but progressive outlook NASA is working towards in incorporating MBSE to its SE approach. Some of the growing pains with MBSE were referenced as putting in more time than it seemed to be worth for some aspects of each program. While this is a valid argument, the teams perhaps underestimate the learning curve and exponential savings they gain as they become more familiar with MBSE processes and the different ways of visualizing data. Both programs approved of MBSEs versatility as it could easily show highly technical details or big-picture system design elements. Both projects, and different divisions within NASA, seem open to the continued deployment of MBSE at various levels across a wide range of their products. Members across NASA are grasping the potential of applying MBSE while working through early growing pains to tailor it to their specific programs and what they may have use for to allow MBSE to save the enterprise time, money, and scheduling deficits.

##### References

1. J. B. Holladay, J. Knizhnik, K. J. Weiland, A. Stein, T. Sanders, and P. Schwindt, “MBSE Infusion and Modernization initiative (MIAMI): “Hot” Benefits for Real NASA Applications,” *2019 IEEE Aerospace Conference,* Big Sky, MT, USA, 2019, pp. 1-14.
2. K. Bhasin, P. Barnes, J. Reinert, and B. Golden, “Applying model based systems engineering to NASAs space communications networks,” *2013 IEEE International Systems Conference (SysCon),* pp. 1-32, 2013.
3. K. M. Gough and N. Phojanamongkolkij, “Employing Model-Based Systems Engineering (MBSE) on a NASA Aeronautic Research Project: A Case Study,” *2018 Aviation Technology, Integration, and Operations Conference,* pp. 1-15, Jun. 2018.
4. N. Phojanamongkolkij, K. Lee, S. T. Miller, K. A. Vorndran, K. R. Vaden, E. P. Ross, R. C. Powell, and R. Moses, “Modeling to Mars: A NASA Model Based Systems Engineering Pathfinder Effort,” *AIAA Space and Astronautics Forum and Exposition,* pp. 1-15, Sep. 2017.
5. S. Rhodes and J. Hale, “Second International Workshop on MBE,” *III-Vs Review,* vol. 9, no. 4, pp. 63-64, 1996.