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How the INCOSE Model-Based Capability Matrix Has Steered Model-Based Systems Engineering Transformation at NASA

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Abstract. The National Aeronautics and Space Administration (NASA) is embarking on new, complex, and diverse missions to accomplish its scientific and exploration objectives, and it views digital transformation as a key enabler for those missions. The NASA Model-Based Systems Engineering (MBSE) Leadership Team (MLT) is leading the charge in the digital transformation of the systems engineering domain at NASA, and it is using the INCOSE Model-Based Capability Matrix (MBCM) as a roadmap. This paper discusses the modifications and tailoring of the INCOSE MBCM (Hale & Hoheb, 2020) for use at NASA, the process the team has taken on multiple rounds of assessment, findings to date, and work products that have been generated as a result of the assessment. The paper will also discuss findings and potential changes that should be made to the original product.

Keywords. MBSE, digital engineering, MBCA, MBCM.

Introduction

NASA began the MBSE journey in the early 2000's but was limited to grassroots efforts at the engineer level. It was not until 2009 that NASA began exploring more formal model-based approaches through an agency-level SE working group and initiated the NASA Integrated Model-centric Architecture (NIMA) initiative in 2011, which ran until 2015. In 2015 the NASA Systems Engineering Technical Fellow decided to investigate MBSE implementation more deeply to allow NASA systems engineers the opportunity to become "smart buyers" for the eventual rollout of MBSE to the Agency. Later in 2016 the MBSE Infusion and Modernization Initiative (MIAMI) was started along with the Agency's MBSE Community of Practice. The goal of MIAMI was to annually select a few relevant NASA projects to apply MBSE methodologies and best practices with representatives from the different field centers to test and demonstrate viability and efficacy within the Agency. MIAMI ran until the end of the government fiscal year (FY) 2018 when the recommendations to roll MBSE out as part of NASA's core engineering competencies was made to senior leadership in October of 2019 and the formulation of the NASA MBSE Leadership Team (MLT) took place in February of 2020 (Hill et al, 2024).

As stated in INCOSE Vision 2035 (2022):

> *By 2035, systems engineering will leverage the digital transformation in its tools and methods, and it will be largely model based using integrated descriptive and analytical digital representations of the systems. Systems design, analysis, and simulation models, immersive technologies, and an analytic framework will enable broad trade-space exploration, rapid design evolution, and provide a shared understanding of the system throughout its life cycle.*

The primary digital transformation goals within NASA's Engineering domain center around the more effective data-centric flow and management of information in support of standardized engineering and business/institutional processes and workflows (with the required data/information constructs and meta data needed for maximum benefit). Using integrated toolchains and associated digital threads across the system lifecycle will enable programs and projects to decrease the time required to define mission architectures and designs, reduce design errors and later rework, facilitate change impact analysis, and enable data-centric management of all data and information associated with engineering products, services, design, and associated artifacts (Hill et al, 2024).

To better understand the Agency's MBSE workforce maturity, processes, and tool usage, in late 2020 an external maturation scale was sought which led NASA to undertake utilizing a tailored version of *INCOSE MBCM and User's Guide* (Hale & Hoheb, 2020). The MLT recognized the need for organization and providing structure to the myriad digital transformation activities occurring across the Agency, and it saw the promise of such structure in the actionable metrics of the INCOSE MBCM. The following paper will elaborate on a portion of NASA's MBSE development path, the roll the Model-Based Capability Assessment (MBCA) played, how NASA has used the resulting insights, and the changes to the MBCA NASA made to better inform the Agency's maturity assessment and progress.

INCOSE Model-Based Capability Matrix

The INCOSE MBCM is an organizational assessment tool that can be used to characterize the current and targeted maturity of the organization's capabilities for MBSE. It was developed by a Challenge Team of the MBSE Initiative, which is sponsored by INCOSE and the OMG (Object Management Group). The INCOSE MBCM is accompanied by a User's Guide (Hale & Hoheb, 2020) that offers recommendations on tailoring the matrix, performing assessments, analyzing the results, and how it might be used for the planning of capability improvement activities.

The released INCOSE MBCM defines 42 capabilities that are sorted into 8 categories: 1. Workforce/Culture, 2. SE Processes/Methodology, 3. Program/Project Processes Methodology, 4. Model Based Effectiveness, 5. Information Technology Infrastructure, 6. Modeling Tool Construction, 7. Model Use, and 8. Modeling Policy. It defines five levels of maturity for each capability – Stage 0 through Stage 4. While the specifics vary by capability, the general pattern is Stage 0 represents an ad hoc or absent practice. Incremental improvements are made for each stage until the capability is consistently applied across the organizational enterprise.

In late calendar year 2020 NASA first utilized the INCOSE MBCM to assess the usefulness of the information collected as part of the assessment. It was determined to be informative, but some areas were too industry-specific, and so NASA's subsequent tailoring of the MBCM maintained the intent of each capability while customizing the content to reflect NASA's defined SE processes and address areas that needed more clarity. The tailoring and modifications are discussed further in this paper.

Assessment Results

Phase I

Phase I of the NASA MBCA was performed in early 2021. The intent was to collect an initial set of center-level data from across NASA as quickly as possible and if the MBCA was even a viable approach for NASA. The MLT needed a quick assessment to guide their planning efforts and to identify where opportunities existed for 'lift-and-shift' of capability. The specific approaches were left to the MLT center representatives, but they were encouraged to keep the assessment team small. They were often performed by a single well-informed individual. Phase I involved participation from nine of the ten NASA field centers. The Phase I center-level results are summarized by Table 1.

Table 1. Phase I NASA MBCA Result Summary – Center Score Heatmap

Model-Based Capability Categories	NASA Average	ARC	GRC	GSFC	JPL	JSC	KSC	LaRC	MSFC	SSC
1. Workforce/ culture	0.5	0.1	1.0	1.1	0.2	0.7	0.7	0.5	0.5	0.0
2. SE Processes	0.5	0.6	0.2	0.8	0.5	0.4	0.4	0.9	0.4	0.0
3. Program/ Project Processes	0.3	0.4	0.4	1.1	0.0	0.0	0.3	0.7	0.0	0.0
4. Model Based Effectiveness	0.6	0.8	0.5	0.9	0.0	0.5	0.3	1.0	0.6	0.3
5. Information Technology Infrastructure	1.6	2.5	1.6	2.2	1.5	1.5	0.7	2.6	1.8	0.2
6. Modeling Tool Construction	0.4	0.2	0.4	1.1	0.0	0.3	0.4	0.9	0.2	0.1
7. Model Use	0.4	0.0	1.0	1.0	0.0	0.0	0.5	0.7	0.3	0.0
8. Modeling Policy	1.1	0.0	0.0	2.9	2.8	1.5	0.4	0.6	1.6	0.0

Phase II

Phase II of the MBCA was performed in the middle of 2021, immediately after Phase I. The intent was to refine and formalize the quickly collected initial results. Each Center was tasked with ensuring the assessment was representative of the entire center and to involve stakeholders sufficient to make that determination. The Phase II center-level results are summarized by Table 2. A comparison of the center-level results and the vanguard results are summarized by the radar plots in Figure 1. These views illustrate that while the institutional MBSE capabilities at NASA centers are modest and mostly *ad hoc*, there are pockets of expertise across the Agency that collectively represent advanced stages of execution. This difference represents many exciting opportunities.

Table 2. Phase II NASA MBCA Result Summary – Center Scores

2021	AFRC	ARC	GRC	GSFC	JPL	JSC	KSC	LaRC	MSFC	SSC	NASA
1. Workforce/ culture	0.0	0.1	1.0	1.1	0.2	0.7	0.3	0.5	0.7	0.0	0.5
2. SE Processes	0.0	0.4	0.2	0.8	0.5	0.4	0.4	0.9	0.6	0.0	0.4
3. Program/ Project Processes	0.0	0.4	0.4	1.0	0.0	0.0	0.4	0.7	0.0	0.0	0.3
4. Model Based Effectiveness	0.0	0.8	0.5	0.9	0.0	0.5	0.3	1.0	0.3	0.3	0.5
5. Information Technology Infrastructure	0.0	2.1	1.6	2.2	1.5	0.9	0.7	2.6	3.2	0.2	1.5
6. Modeling Tool Construction	0.0	0.0	0.4	1.0	0.0	0.3	0.4	0.9	0.3	0.1	0.3
7. Model Use	0.0	0.0	0.8	0.8	0.0	0.0	0.4	0.6	0.3	0.0	0.3
8. Modeling Policy	0.0	0.0	0.0	3.0	2.9	1.9	0.5	0.5	3.1	0.0	1.2
NASA	0.0	0.4	0.6	1.1	0.4	0.5	0.4	0.9	0.8	0.1	0.5

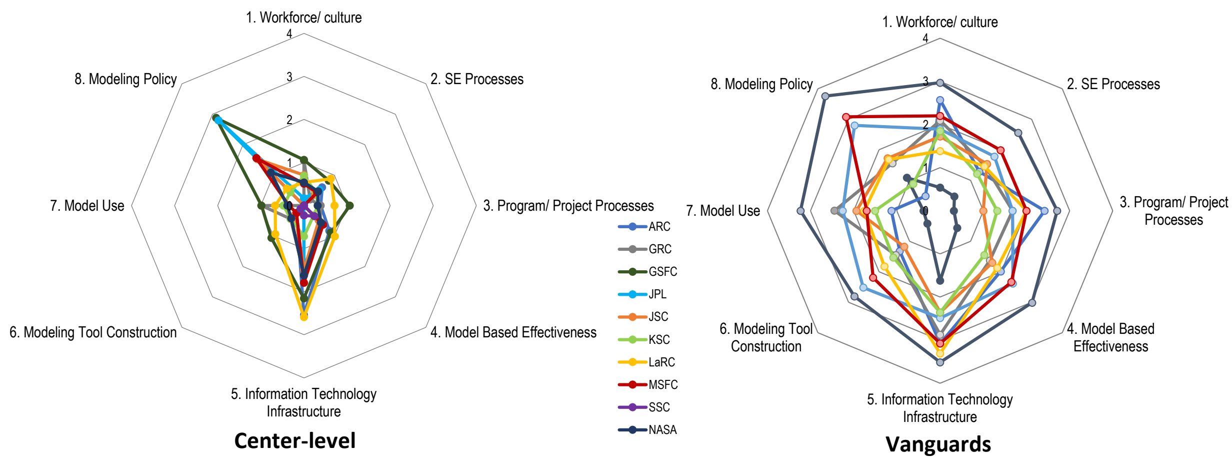


Figure 1. Phase II Results – Center and Vanguard Averages

This round of assessment also introduced the Vanguard Projects list, which was used to link projects to the specific center capabilities they drive. The product was a structured dataset of over 60 vanguard projects with full traceability to the capabilities they lead. This has allowed the MLT to efficiently identify the Agency-wide experts and leaders in each capability area.

A comparison of the results of phases I and II do show some differences in the details, but the aggregated results were very similar. Phase II ultimately validated the initial conclusions made after Phase I with scores of higher pedigrees. This meant the MLT had more confidence in the plans they had created, and it gave their subsequent proposals more of a mandate. It does also demonstrate, however, that lightweight assessments made by a small team may be 'good enough' for many organizations.

Phase III

Phase III of the MBCA was conducted in late 2023. The intent was to update the assessment to gauge progress across NASA and to inform the MLT's work plans going forward. Prior to this updated assessment, the MLT revisited the definitions of the matrix – see the previous decision of the 2023 NASA MBCA update above. The Phase III results are summarized in Table 3, and can be compared to the Phase II results, which is summarized by Figure 2. MBCA Comparison - 2021 to 2023. The average center-level scores show a positive trend in all categories and are making progress towards the initial goals set by the MLT (shown as the "Goal 1" series in Figure 2). The Center Max series represents the highest center-level score for each capability, and this saw a large jump in maturity. This highlighted where NASA centers have implemented new policies, processes, methods, tools, or workforce enrichment programs that have had significant impacts on their ability to implement MBSE. These areas are being mined for opportunities to lift these center-level improvements and apply them across the Agency. The vanguard scores shown also represent the maximum score from across all centers, and overall, these also made meaningful progress. The average for Category 3, *Program/Project Processes*, shows a reduction in the overall vanguard scores across NASA, and this attributable to a single project that was scored too aggressively upon reassessment; there was no actual regression of maturity.

Because the matrix was modified for this round of assessment, there were some changes to scores attributable to the scorecard being changed instead of a change in maturity. While no effort has been made to isolate this effect, and the scores from the previous rounds were not reassessed, the perception of the team is the effort is ultimately neutral.

Table 3. Phase III NASA MBCA Result Summary – Center Scores

2023	AFRC	ARC	GRC	GSFC	JPL	JSC	KSC	LaRC	MSFC	SSC	NASA
1. Workforce/ culture	0.0	0.4	2.6	1.1	0.8	1.3	1.2	1.0	1.1	0.0	1.0
2. SE Processes	0.0	0.6	1.6	0.8	1.4	0.6	0.6	1.2	0.3	0.0	0.7
3. Program/ Project Processes	0.0	0.7	2.4	1.0	1.4	0.0	0.4	0.7	0.0	0.0	0.7
4. Model Based Effectiveness	0.0	0.8	1.6	0.9	2.2	0.8	0.6	1.1	0.2	1.7	1.0
5. Information Technology Infrastructure	0.0	2.3	2.5	2.2	2.0	0.9	2.8	2.5	3.2	0.8	1.9
6. Modeling Tool Construction	0.0	0.3	1.7	1.0	1.2	0.6	1.0	1.3	0.3	0.9	0.8
7. Model Use	0.0	0.3	1.5	0.8	0.7	0.4	0.7	0.7	0.5	1.1	0.7
8. Modeling Policy	0.0	0.2	1.1	3.0	2.1	1.9	0.5	1.5	2.8	1.2	1.4
NASA	0.0	0.6	1.8	1.1	1.4	0.7	0.9	1.2	0.7	0.7	0.9

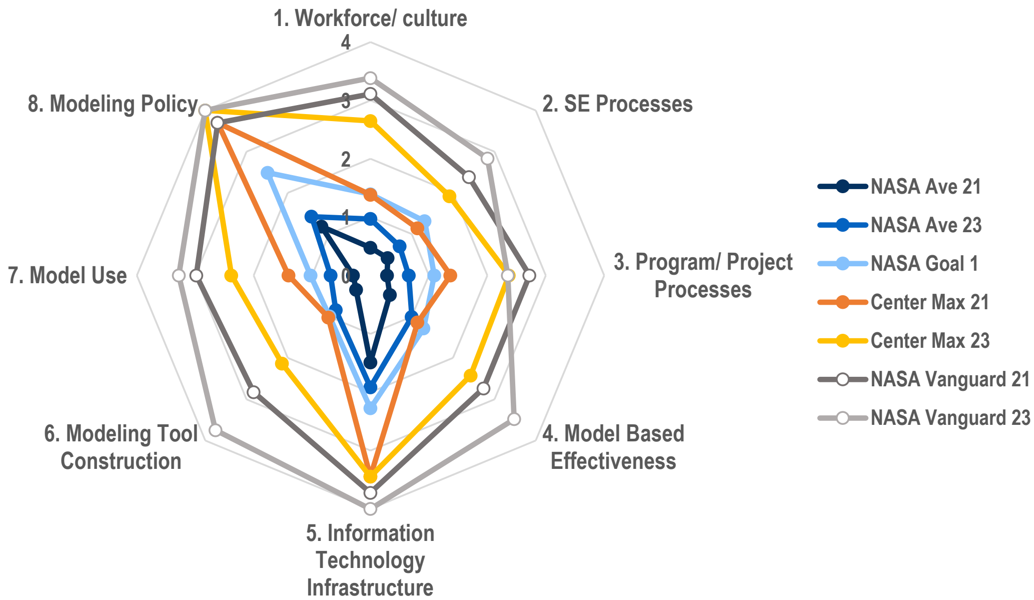


Figure 2. MBCA Comparison - 2021 to 2023

MBCA-Driven Activities & Products

The MLT is organized into three sub-teams: Workforce, Processes, and Tools. This organizational structure aligns with the people, process, technology framework (three-legged stool/golden triangle) that has been around for decades. This framework allows the team to focus on the individual components and ensure integration across the engineering functions. The framework has been successfully used to instantiate organizational change which is necessary to ensure that MBSE and digital engineering are employed across the Agency. The MLT relies on the MBSE Community of Practice (CoP), the Agency-wide community of MBSE practitioners, to build consensus and awareness in the planning and the results needed to increase the overall capability. Using the data from Phase I and II, the MBCA capabilities were assigned to a sub-team to determine: the work required to increase the score of the capability; the priority of delivering the capability; where the Agency would invest time/funding to decrease the barrier to entry for that capability; and where the hand-off to institutional workforce should occur. This plan was executed and resulted in the increased capabilities that are seen in Phase III. A summary of the work completed is detailed in the sections below.

Workforce Sub-Team

The workforce sub-team initially focused on the capabilities in the category of workforce/culture that centered around training, roles and responsibilities, and model development skills.

The first step was benchmarking different organizations from industry, government, and academia to gain an understanding of MBSE use, modeling development skills, modeling roles and responsibilities, and training practices. Academia benchmarking was focused on how MBSE is integrated into their overall approach and curriculum and their definition of MBSE learning objectives. Industry/government benchmarking focused on: how well MBSE has been adopted and implemented into their programs/projects; and the content and implementation of training and development programs for MBSE.

The benchmarking activity supported:

- Creation of a website that contains links to the available training material, videos, and courses.
- Definition of the expected skill levels (Level 1-5) based on tasks/functions performed.
- Modification of the requirements for MBSE formal training and aligned it with Levels 1-5.
    - Four advanced classes were added to the curriculum.
- Definition of roles, including non-modelers that need to support MBSE, and mapping them to training and expected skill level.

This work is contributed the maturation of the model-based capabilities in the areas of Workforce/Culture from a NASA average of 0.5 in Phase I to an average of 1.0 currently.

Future work for this team will focus on common terminology, MBSE usage and policies, and further refinement of training requirements.

Processes Sub-Team

The processes sub-team initially focused on capabilities in the categories of *SE* and *Program/Project Processes* that centered on the crosscutting processes and those that support the concept development phase.

NASA Procedural Requirement (NPR) Modeling. The major undertaking of this team was to convert the document, text-based procedural requirements into an integrated process model. The NPR modeling focused on the NPRs that contained the procedural requirements for the SE (7123.1) and Program/Project Processes (7120.x). This identified effort aligned with Office of Safety and Mission Assurance's process modeling that they wanted to undertake for risk classification (8705.x), which is also identified as part of the cross-cutting SE and integration aspects. This project was divided into three phases: As-Is, Analysis, and Transform, and is currently at the end of the Analysis Phase. More information can be found in *Modeling NASA's Procedural Requirement Processes - Implications for Digital Future* (Nicoli, et al., 2024). This work is contributing to the maturation of the model-based capabilities in the areas of *SE* and *Program/Project* process from a NASA average of 0.3 and 0.4 respectively in Phase I to an average of 0.7.

Digital Artifacts: The process team realized that the inputs/outputs of the processes as they exist today are documents. The COP was asked to engage and undertook a series of work topics to advance the maturity of process-related MBCA capabilities. Topics completed to date are *Technical Requirements Definition*, *Configuration Management*, and *Stakeholder Expectations*. Upcoming topics include *Verification & Validation* and *Interface Management*. The standard process for the CoP work topic was to review the topic against the MBCA maturity stage definitions and solicit additional input from the Vanguards identified in the MBCA. A generalized approach was applied to each topic. The model resources to support program/project implementation were developed and reviewed by the CoP and were made available to the NASA community via the NASA Engineering Network where all the CoP collaboration areas reside.

Technical Requirements Definition. The first of the MBCA work topics for the NASA MBSE CoP addressed the use of modeling to transform stakeholder expectations into a good set of requirements that can be used for defining the design solution. The focus was the use of SysML system models as opposed to entering records into a requirements management tool. The group shared and compiled examples of requirements definition, requirements validation, and the connections and dependencies to related processes. This was followed by the generation of templates and example digital artifacts to support the process that are shown in Figure 3. The model-based requirements section of their wiki guide was also revamped. This work contributed to the maturation of the model-based requirements definition capability across NASA from an average MBCA rating of 0.6 (a mix of Stages 0 and 1) at Phase II to an average of 1.0 (a mix of Stages 1 and 2). To attain Stages 3 and 4, NASA will need a more robust *Digital Thread* capability and increase the prevalence of executable system models and digital twins.

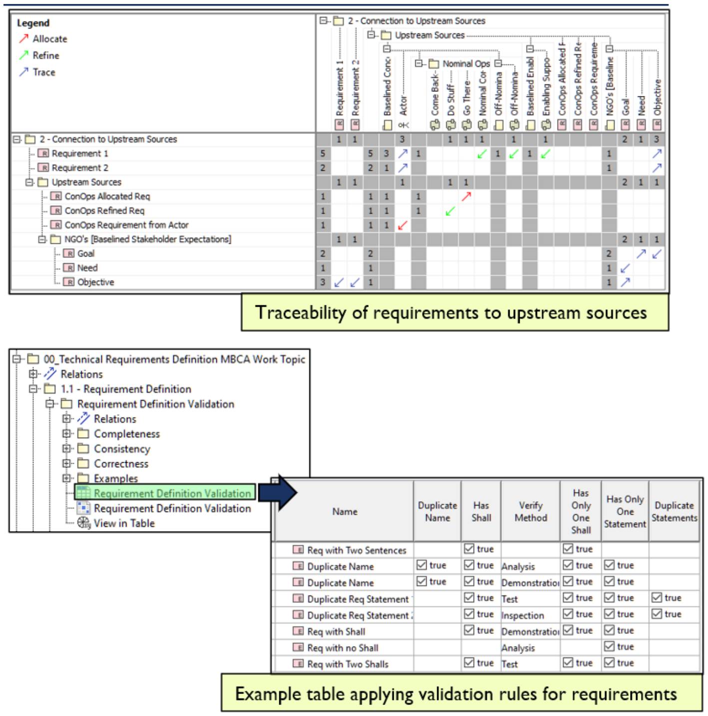


Figure 3. Requirement Definition Process Traceability and Validation

Configuration Management. The second work topic captured how the Configuration Management (CM) process relates to MBSE and the CM of models. After a similar process of sharing and collaboration, the group produced a new set of examples and instructional materials. The biggest improvement was in the rework of the CM portion of NASA's modeling plan template. This will accelerate NASA organizations in maturing their *Model Configuration Management* capability to at least Stage 2. It also contributes to the maturation of several other MBCA capabilities, especially *Authoritative Source of Truth*, which requires the identification of configuration items for Stage 1.

Stakeholder Expectations. The most recent MBCA work topic addressed the *Modeling Stakeholder Expectations* capability, including the development of needs, goals, objectives, concepts of operation, and other related artifacts. This activity relied heavily on the identification of the MBCA vanguard projects and inviting each to share their experiences and best practices. These inputs were used to create and update reference material, templates, and tool export reports; see Figure 4. The work also validated the NASA SE Metamodel documented in NASA-HDBK-1009, NASA Systems Modeling Handbook for Systems Engineering (2022). This work enables projects to execute at a Stage 2; as with requirements, further maturity depends on *Digital Threads* and executable system models.

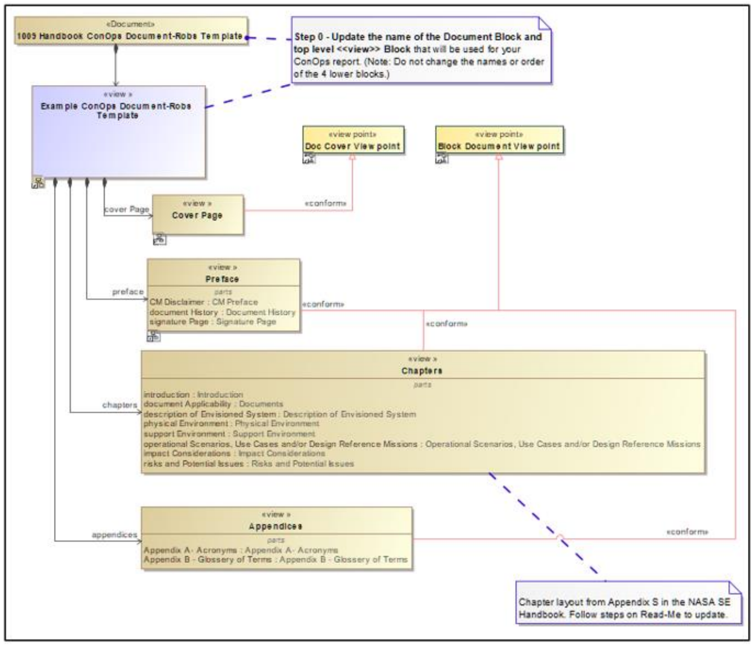


Figure 4. Concept of Operations Report Model

Digital Twin Pilot Project. Members of the MLT executed a Digital Twin pilot project to advance the capability for digital twin implementation at NASA while aiding a major NASA program address their insight issues. The focus was on developing a working digital twin of the spacecraft's electrical power subsystem in a SysML environment to demonstrate the utility of evolving an early lifecycle architecture description model to an executable systems model and eventually a digital twin connected to a physical asset. One outcome of the project is the concept of "twininess", which refers to the extent, by both scope and degree, a system model is a digital twin. This emphasizes the importance of understanding desired use cases, driving system characteristics, and the needed technical capabilities needed to realize the connected model. The result is a direct impact to the maturity of the Digital Twin MBCA Capability at NASA. For more information, refer to *Orion SysML Model, Digital Twin, and Lessons Learned for Artemis I* (Pierce, Heeren, & Hill, 2023).

Tools Sub-Team

The tools sub-team initially focused on the capabilities that in multiple categories that focused on digital thread and toolchains, tool evaluations and their ability to integrate, demonstrations of use cases for connectivity, IT security evaluations, and tool governance.

One of the initials steps was to benchmark the Agency in order to understand the tools and toolchains that are in use at NASA today. The benchmarking leveraged data on software tools that had been collected by the Agency Engineering Portfolio Management Board. The benchmarking expanded on the data to understand how the tools in the portfolio were connected and used. Tools that were common and used most across toolchains are being evaluated, demonstrated. One of the major issues identified is the lack of common standards for data transformation that would increase tool and data interoperability. This finding has led to increased engagement with other government agencies, industry, and professional societies to have a better understanding of upcoming changes to standards and state of the art implementations.

Assessment Methodology

The NASA MLT Center representatives led the local assessments with the tailored matrix and reported results back for analysis. The NASA MBCA lead coordinated the overall assessment as well as developed tools, first in Microsoft Excel and later in PowerBI, to aggregate and analyze the Agency results. The initial Phase I assessment was on a small scall to expedite results and to demonstrate value, and this was followed immediately by a Phase II, which was a broader, more collaborative assessment involving more stakeholders. The MBCA will be repeated periodically to update results, learn new findings, and track progress.

Assessment Structure

Center & Vanguard Ratings. An initial difficulty with applying the MBCM to a diverse organization such as NASA was determining a single score for each capability that was representative of the Agency and the individual NASA centers. The approach taken was to assess capabilities at the NASA center level from two different perspectives. The first perspective is the NASA center-wide capability, meant to capture the institutionally provided processes and infrastructure in place to support projects (NASA MBCA Phase I). The second perspective centered around vanguard capabilities to identify where there is at least one project or organization operating at a higher maturity (Phase II). This vanguard rating is an aggregate that does not necessarily represent a single project as different projects may be used for each capability. The MLT found this to be a powerful way to honestly capture the institutional maturity while also illuminating areas of advanced ability and practice, which represent opportunities for growth across the Agency.

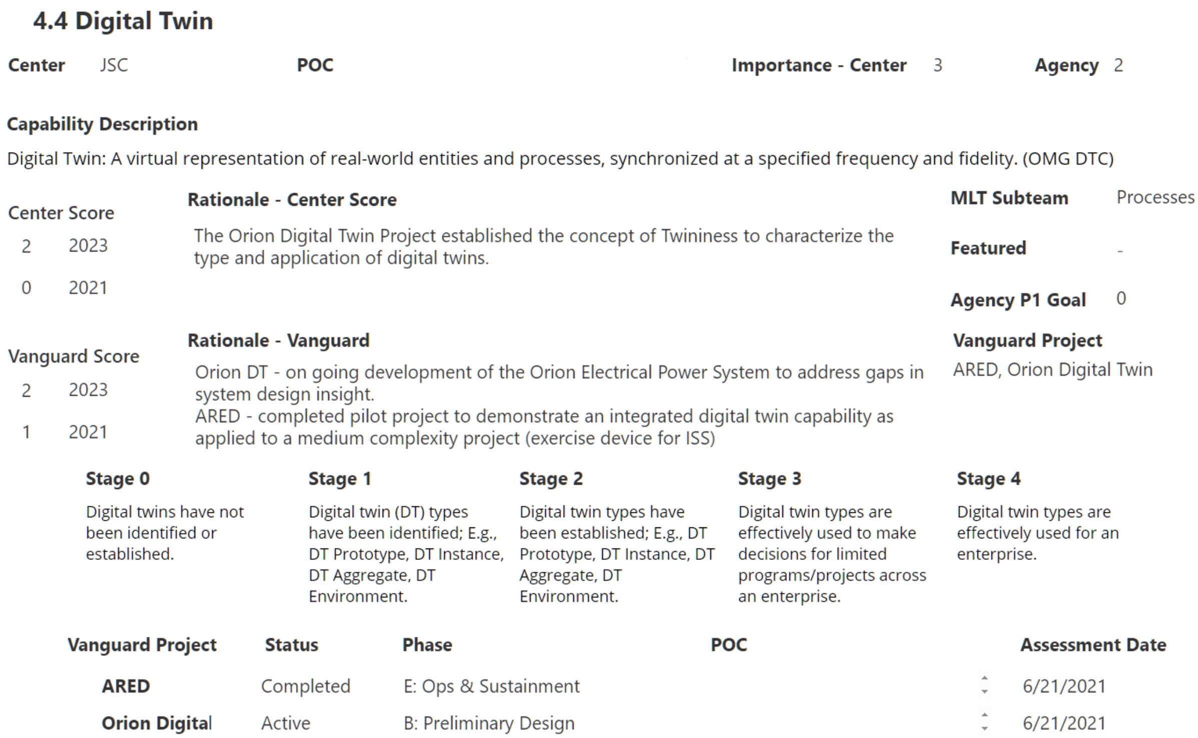
Importance. The team did not view every capability equally, so an Importance rating (1-Low to 5-High) was added. The center-level Importance ratings were aggregated at the NASA level through a simple average, which is used as the weighting factor in category roll-ups. The Importance scores have since been used in FY23 and FY24 to inform strategic planning and to prioritize funding to activities and projects.

Rationale. The justification for each rating, both center-level and vanguard, was captured. As suggested by the INCOSE MBCM User's Guide, capturing the reasoning and story behind the scores is the source of much of the benefit of performing these assessments. The experience of the NASA MLT validates this finding.

Vanguard Projects. As MBSE-advanced projects were identified, they were captured in the MBCA database along with key information, which included the current project phase, points of contact, whether the project is completed, the NASA center(s) involved, and a summary of the project's contributions to MBSE. These projects were then linked to the respective MBCA capabilities.

SharePoint Environment. While center inputs where manually compiled via spreadsheets in Phase I, the MBCA was migrated to the NASA Microsoft SharePoint environment. This allowed each center to actively update their own data in the same common environment.

Three lists were used for the MBCA. The first captured the matrix itself along with any Agency-level details such as average importance. The second contained the set of ratings and rationales for each capability and NASA center; this also contained the links to the other lists. The third was the vanguard projects list. A custom data entry form was created using Microsoft PowerApps to display information pulled in from all three lists. This offered a better user experience than the previous spreadsheets. An example of this is shown in Figure 5. Hosting the data in SharePoint also allowed the team to co-locate guidance materials and dashboards for results inspection.



4.4 Digital Twin

Center JSC **POC** **Importance - Center** 3 **Agency** 2

Capability Description

Digital Twin: A virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity. (OMG DTC)

Center Score		Rationale - Center Score
2	2023	The Orion Digital Twin Project established the concept of Twininess to characterize the type and application of digital twins.
0	2021	

MLT Subteam Processes

Featured -

Agency P1 Goal 0

Vanguard Score		Rationale - Vanguard
2	2023	Orion DT - on going development of the Orion Electrical Power System to address gaps in system design insight. ARED - completed pilot project to demonstrate an integrated digital twin capability as applied to a medium complexity project (exercise device for ISS)
1	2021	

Vanguard Project

ARED, Orion Digital Twin

Stage 0	Stage 1	Stage 2	Stage 3	Stage 4
Digital twins have not been identified or established.	Digital twin (DT) types have been identified; E.g., DT Prototype, DT Instance, DT Aggregate, DT Environment.	Digital twin types have been established; E.g., DT Prototype, DT Instance, DT Aggregate, DT Environment.	Digital twin types are effectively used to make decisions for limited programs/projects across an enterprise.	Digital twin types are effectively used for an enterprise.

Vanguard Project	Status	Phase	POC	Assessment Date
ARED	Completed	E: Ops & Sustainment		6/21/2021
Orion Digital	Active	B: Preliminary Design		6/21/2021

Figure 5. Data Entry Form

Assessment Approaches

The specifics for how to arrive at Center and Vanguard scores was at the discretion of the MBCA assessment leads. Techniques included:

Expert Assessment & Community Review. In this approach, maturity for each capability was assessed by an individual or small group of experts. This product was then routed for review by a broader set of stakeholders in the community. There were several iterations over customization, scope, and terminology which resulted in greater clarity and enabled better evaluation efforts. This lightweight approach achieved Agency-wide consensus in the scores with minimal effort by stakeholders.

Panel Assessment. A moderately-sized group of experts and stakeholders with broad representation from the modeling community of the NASA center determined the maturity for each capability during one or more workshop sessions. While this required a more significant time commitment from the community, it provided the added benefits inherent to group discussion. It was also a valuable source of community building. This approach is very similar to that recommended by the INCOSE MBCM team (Hale & Hoheb, 2020).

Vanguard Project Assessment. This approach applied the MBCA assessment to individual projects as well as to the center overall. Here, one of the above techniques is used to arrive at a Center Score, but the Vanguard score for each capability was the highest of any of the assessed projects. This provided direct benefits to the projects to which it was applied, and it improved the quality of the overall assessment. It also enabled sharing of efforts on the forefront. The downsides are the added effort required and the use of an assessment tool tailored for enterprise use to a single project.

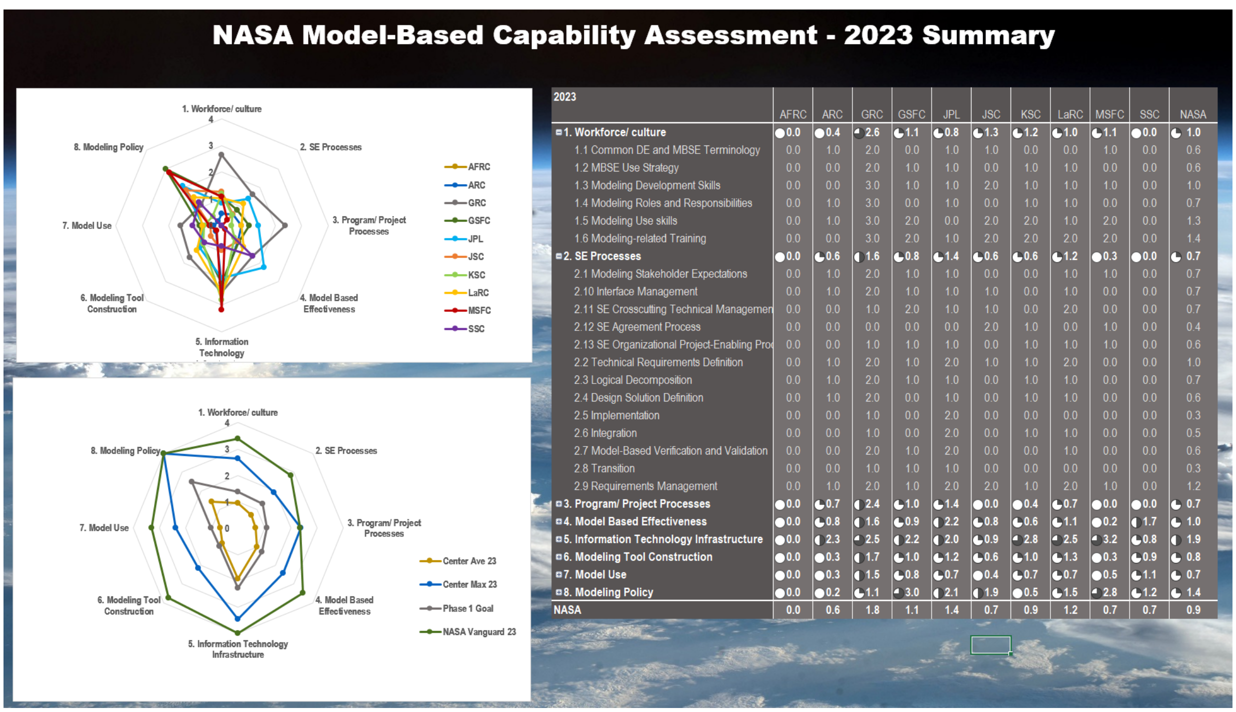
Analysis Techniques

Averaging Technique. With ten NASA centers and eight categories to integrate and summarize, it was necessary to deploy some aggregation methodology. While the averaging of ordinal numbers is never ideal, in this case, it provided insight when combined with a radar plot (see below). This lightweight method was an efficient way to gauge overall status. While NASA Centers were assigned equal weight for averaging purposes, not every MBCA capability was seen as equal, and so the net Importance rating of each capability was used as a weighting factor; see Equation (1) below, where I_i is the Importance rating and S_i is the MBCA maturity score. The Importance rating used here is the simple average of Importance inputs collected from the center-level assessments.

$$Wave = \frac{\sum_{i=1}^{n} I_i S_i}{\sum_{i=1}^{n} I_i} \tag{1}$$

Measures. Several measures and aggregations were found to be useful by the team, including averages of each category, center, and NASA overall, as well as maximums (highest rating within a defined context), deltas (change in rating from one phase to another), and deviations (difference in a rating from the prevailing average).

MS Excel Power Pivot & MS PowerBI. At various times, both Microsoft Excel, with its Power Pivot add-in (see Figure 6), and Microsoft PowerBI (see Figure 7) were used by the MLT to perform its analysis and for stakeholders to review the information. In both cases, the reports were easily updated from the source data on SharePoint – Power Query was used to pull the latest information from the three SharePoint lists and transform the data as needed for the reports, but a user command is required to initiate a data refresh. The Power Pivot Data Manager was then used to add derived and calculated columns, calculated measures, and table relationships. The subsequent data model was used to drive the pivot tables and charts shown in the reports.



2023	AFRC	ARC	GRC	GSFC	JPL	JSC	KSC	LaRC	MSFC	SSC	NASA
1. Workforce/ culture	0.0	0.4	2.6	1.1	0.8	1.3	1.2	1.0	1.1	0.0	1.0
1.1 Common DE and MBSE Terminology	0.0	1.0	2.0	0.0	1.0	1.0	0.0	0.0	1.0	0.0	0.6
1.2 MBSE Use Strategy	0.0	0.0	2.0	1.0	1.0	0.0	1.0	1.0	0.0	0.0	0.6
1.3 Modeling Development Skills	0.0	0.0	3.0	1.0	1.0	2.0	1.0	1.0	1.0	0.0	1.0
1.4 Modeling Roles and Responsibilities	0.0	1.0	3.0	0.0	1.0	0.0	1.0	1.0	0.0	0.0	0.7
1.5 Modeling Use skills	0.0	1.0	3.0	2.0	0.0	2.0	2.0	1.0	2.0	0.0	1.3
1.6 Modeling-related Training	0.0	0.0	3.0	2.0	1.0	2.0	2.0	2.0	2.0	0.0	1.4
2. SE Processes	0.0	0.6	1.6	0.8	1.4	0.6	0.6	1.2	0.3	0.0	0.7
2.1 Modeling Stakeholder Expectations	0.0	1.0	2.0	1.0	1.0	0.0	0.0	1.0	1.0	0.0	0.7
2.10 Interface Management	0.0	1.0	2.0	1.0	1.0	1.0	0.0	1.0	0.0	0.0	0.7
2.11 SE Crosscutting Technical Managemen	0.0	0.0	1.0	2.0	1.0	1.0	0.0	2.0	0.0	0.0	0.7
2.12 SE Agreement Process	0.0	0.0	0.0	0.0	0.0	2.0	1.0	0.0	1.0	0.0	0.4
2.13 SE Organizational Project-Enabling Proc	0.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	0.0	0.6
2.2 Technical Requirements Definition	0.0	1.0	2.0	1.0	2.0	1.0	1.0	2.0	0.0	0.0	1.0
2.3 Logical Decomposition	0.0	1.0	2.0	1.0	1.0	0.0	1.0	1.0	0.0	0.0	0.7
2.4 Design Solution Definition	0.0	1.0	2.0	0.0	1.0	0.0	1.0	1.0	0.0	0.0	0.6
2.5 Implementation	0.0	0.0	1.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.3
2.6 Integration	0.0	0.0	1.0	0.0	2.0	0.0	1.0	1.0	0.0	0.0	0.5
2.7 Model-Based Verification and Validation	0.0	0.0	2.0	1.0	2.0	0.0	0.0	1.0	0.0	0.0	0.6
2.8 Transition	0.0	0.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.3
2.9 Requirements Management	0.0	1.0	2.0	1.0	2.0	2.0	1.0	2.0	1.0	0.0	1.2
3. Program/ Project Processes	0.0	0.7	2.4	1.0	1.4	0.0	0.4	0.7	0.0	0.0	0.7
4. Model Based Effectiveness	0.0	0.8	1.6	0.9	2.2	0.8	0.6	1.1	0.2	1.7	1.0
5. Information Technology Infrastructure	0.0	2.3	2.5	2.2	2.0	0.9	2.8	2.5	3.2	0.8	1.9
6. Modeling Tool Construction	0.0	0.3	1.7	1.0	1.2	0.6	1.0	1.3	0.3	0.9	0.8
7. Model Use	0.0	0.3	1.5	0.8	0.7	0.4	0.7	0.7	0.5	1.1	0.7
8. Modeling Policy	0.0	0.2	1.1	3.0	2.1	1.9	0.5	1.5	2.8	1.2	1.4
NASA	0.0	0.6	1.8	1.1	1.4	0.7	0.9	1.2	0.7	0.7	0.9

Figure 6. Excel Report Workbook – Phase III Summary Sheet

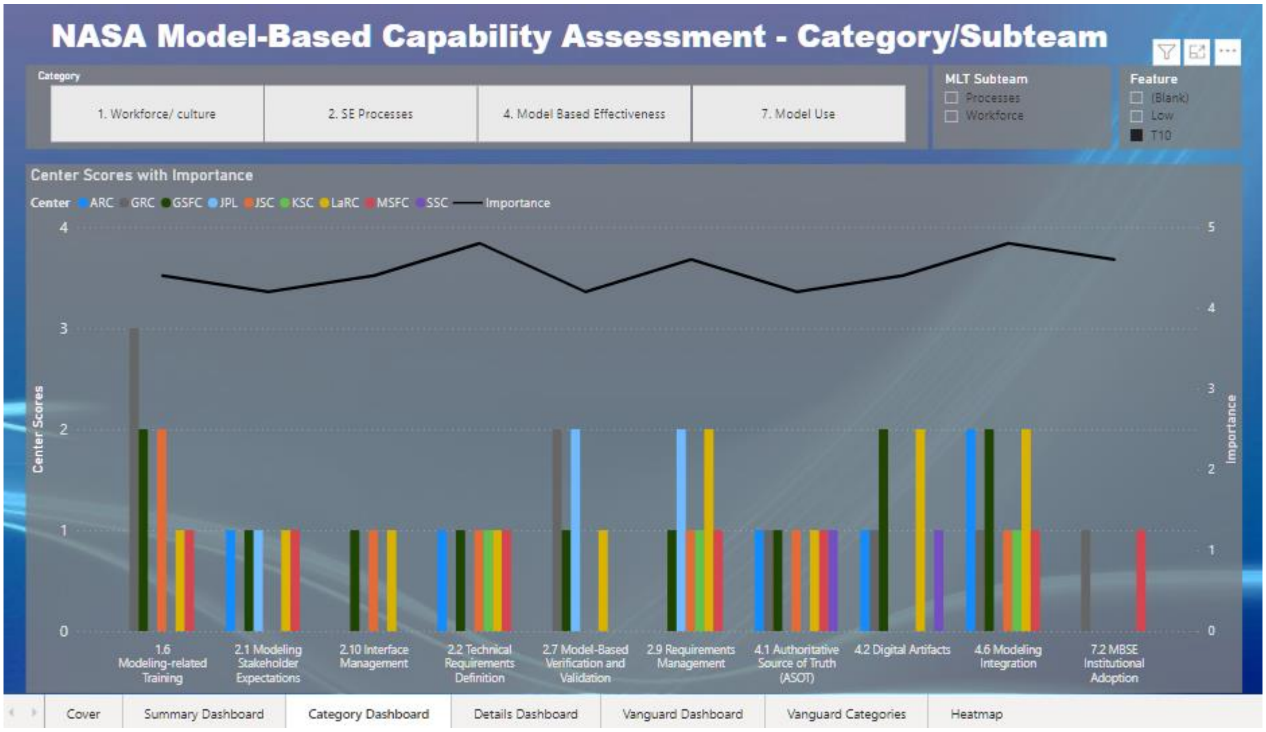


Figure 7. PowerBI Dashboard – Phase II Top 10

Visualizations. With two sets of 50 scores being produced by each of 10 NASA centers, efficient techniques for analyzing and presenting the data to management and other stakeholders is important. One objective was for any report to be autonomously updatable, so the team was limited to the pivot charts and tables. The team found that a radar plot grouped by category gave the viewer a quick impression of the general state of the practice, areas of advanced stages of maturity, and which need extra attention. For example, Figure 1 is useful by quickly showing outliers and clusters of maturity. For detailed analysis, bar charts and tables are more useful; Figure 7. The team employed both 'heatmaps' using color scales, as in Table 1, and the 'pie slices' using icon sets, as in Table 2. Heatmaps were more useful for internal use while the pie slice icons gave a cleaner look for outward presentations.

Tailoring & Modifications

As is encouraged by the INCOSE MBCM User's Guide, the NASA assessment team opted to tailor the assessment matrix. The INCOSE MBCM reflects ISO/IEC/IEEE processes and terms, and while they are similar those used at NASA, the differences led to confusion among stakeholders. Additionally, the team made the following changes (recommended for inclusion when the MBCA is next updated) to increase the emphasis on systems engineering; enhance capability definitions; re-categorized capabilities to maintain more consistent themes; removed requirements for non-MBSE factors; and editorial improvements including correcting typos, removing broken links, and replacing references to inaccessible documents – a detailed discussion of each change follows.

Tailoring

Systems Engineering Engine. For the purposes of the NASA MBCA, changes were made to reflect the NASA Systems Engineering "Engine", as defined by the NASA/SP-2016-6105, *NASA Systems Engineering Handbook* (NASA, 2017). Similarly, all references that define system lifecycle processes were changed from ISO/IEC/IEEE 15288 (ISO/IEC/IEEE, 2023) to the *NASA Systems Engineering Handbook*.

SE Processes Expanded. The INCOSE MBCM capability *SE Technical Processes* was taken to address all systems engineering life cycle processes not otherwise listed, though the capability description suggests otherwise. For more resolution, the NASA MBCA replaces it with *Technical Requirements Definition*, *Requirements Management*, *Interface Management*, *Logical Decomposition*, *Design Solution Definition*, *Implementation*, *Integration*, and *Transition*. With those additions, each facet of NASA's SE engine can be assessed separately. This change was important, as most NASA projects and programs are employing MBSE on a subset of these processes and do so with varying stages of maturity.

Collaboration Capabilities. The *Collaboration Capabilities* capability addresses the way teams can exchange information and contribute to work products, with the maturity ranging from e-mails at Stage 0 to "on-line, real-time collaboration amongst teams for an enterprise" at Stage 4. What was missing was the current practice at NASA, and much of the modeling community, in the use of an on-line model repository system. These systems are significant improvements over the model file exchange of Stage 1 and the centralized but manual model management of Stage 2, but they do not meet the "real-time" criteria needed for Stage 3. To address this, Stage 2 was changed to add "On-line, near-real-time collaboration (such as using tool-managed checkout and synchronization features) within individual model teams."

Model Frameworks. In the INCOSE MBCM, there is not a defined capability for model frameworks. There are several architecture frameworks listed as example languages in the *Model Languages* capability, which was seen as an error. A framework is a way to represent a system and can be implemented in any language. These were simply deleted from the list for the first two phases of the NASA MBCA. For Phase III, a new *Model Frameworks* capability was added to Category 7, *Model Use* to address the need for a standardized set of model viewpoints (or view specifications) to be developed to meet stakeholder needs. It addresses ad hoc views at Stage 0 and matures to a standard framework that is tailored and used across the enterprise at Stage 4.

Quality. The original *Modeling Process Quality* capability caused confusion between the intended meaning of implementing an effective program or project that incorporates modeling with the mistaken meaning of applying modeling to aspects of the Quality discipline. It was renamed *Quality of Modeling Process* as well as other definition clarifications.

Re-Categorization

The analysis of NASA's MBCA relied heavily on the aggregation of information per category. Therefore, it was important to maintain clear definitions of and distinctions between the eight capability categories. Category 2, *SE Processes* ("Methodology" was removed) should focus on the "What" is modeled, so capabilities dealing with "How" of models were moved elsewhere. *Enabling Technologies* is much more closely related to Category 5, *IT Infrastructure*. Category 6, *Modeling Tool Construction*, should not include languages, libraries, or management capabilities. The *MBSE Technical Innovation Process* is closely related to *Tool Governance*, so it was moved to Category 8. The new *Model Frameworks* capability was added to Category 7. The result of several of these moves is Category 7, *Model Use*, now more cleanly captures the degree to which an organization is executing their modeling efforts. All categorization changes are shown in Figure 8.

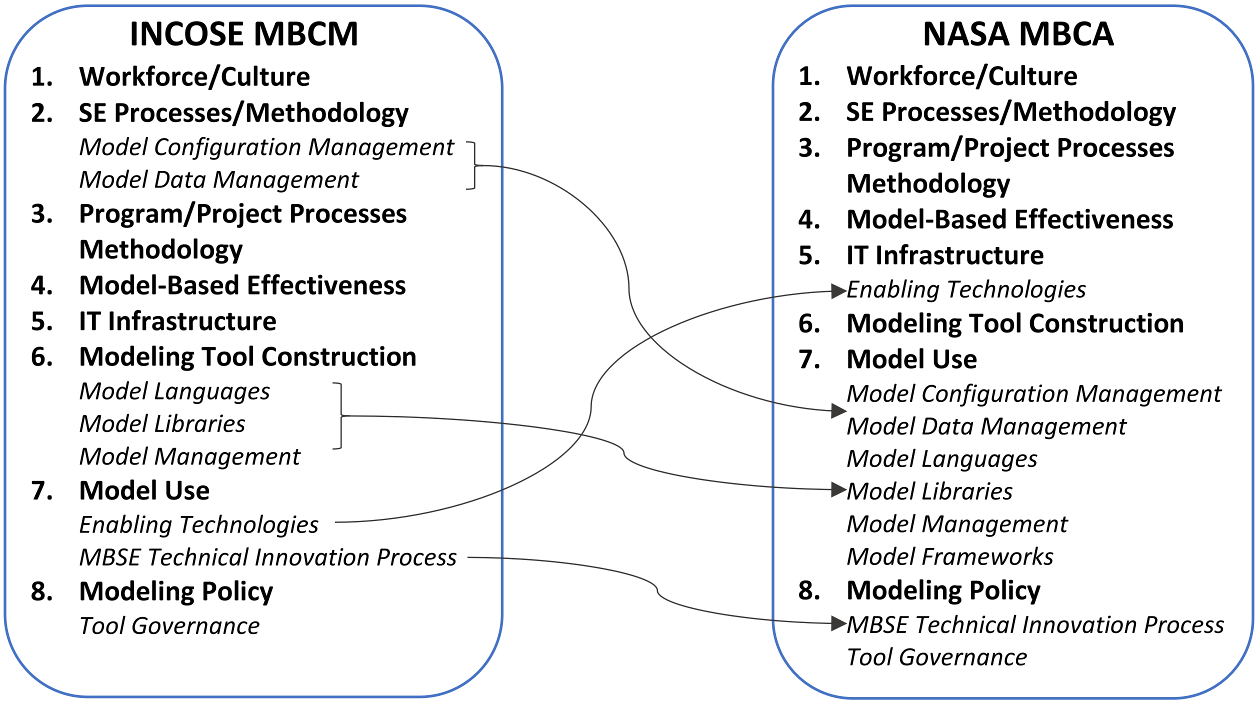


Figure 8. Re-Categorization of Capabilities

Clarifications

In the Spring of 2023 and prior to the assessment for Phase III, the matrix tailoring was revisited to clarify several points of confusion previously experienced. Stakeholders found the changes to be a significant improvement in terms of clearness and precision.

Organizations and Enterprises. Assessment participants experienced significant confusion over the various usages of the words *organization* and *enterprise* in the matrix. In some instances, *organization* and *enterprise* are used interchangeably. In others, *enterprise* refers to the entity that a system of interest participates in to perform a mission, and therefore was itself the subject of modeling. In a third sense, it is used to refer to the entity that an organization participates in to fulfill its organizational goals. These are all appropriate usages of the terms from certain points of view, but asking assessment participants to quickly pivot from one perspective to another was too problematic.

Changes were made to the MBCA such that *organization* refers to the operational unit that is the subject of the MBCA, and usages of *enterprise* as the subject of modeling were changed to *system of interest*. For the remaining instances of *enterprise*, MBCA analysts must determine the most appropriate level to assume on a per-capability basis.

Common Terminology. The capability *Common Digital Engineering and MBSE Terminology* discussed 'known precedence', but it was observed that term provenance is the primary concern, followed by prioritizing alternatives. This capability was reworked to describe a shared glossary of terminology in use by the projects and programs of the organization emerging at Stage 1, where definitions have known sources but may not be unique or unambiguous. The "top tier" terminology still evolves at Stage 2 along with the requirement of precedence for both sets of terms.

Use Strategy. The capability *MBSE Use Strategy* was streamlined to focus on the documented strategy, its reach across the organization, and its consistency with the parent organization. Implications of relationships to the overall risk strategy and integrations with business tools were removed.

Systems Engineering Processes. As previously discussed, the INCOSE MBCM included a single capability, *SE Technical Processes*, to cover much of the lifecycle processes. The maturity stage definitions were consistent with a roll-up capability, being generic and focusing on the degree to which modeling was the basis of the process, the extent to which digital threads connected the digital artifacts associated with the process, and whether digital twins were used to make decisions. In the initial tailoring that separated this one capability into many, this same structure was repeated. The MLT generally liked the approach, but certain things no longer worked when taken out of the context of the single capability. The team found "with digital threads covering all selected processes" needed to be changed to "with digital threads covering the relevant SE processes that are modeled" for Stage 3, implying relationships need to exist where they are both value-added and there is something to which to link. Stage 4 removes the exception "that are modeled". The reference to *digital twins* was also found to be inappropriate for system development lifecycle process such as *Technical Requirements Definition* and *Logical Decomposition*, as most of those processes occur before there are physical assets to connect models to, making true digital twins impossible. These instances of *digital twin* were changed to *executable system model*.

Another observation of the capabilities of Category 2, *SE Processes* is that the lifecycle processes that did get unique treatment by the INCOSE MBCM, specifically *Modeling Stakeholder Requirements* (changed to *Expectations*) and *Model-Based Verification and Validation* were distinct from the 'children' of *SE Technical Processes*. The above changes were merged into the two unique capabilities to improve consistency.

Business Cases. Two capabilities, *SE Agreement Process* and *SE Organizational Project-Enabling Processes*, both focus clear and consistent business cases. It is not clear whether the intent was to refer to a distinct project that business professionals sometimes employ to plan their operations, or to sound rationale for models demonstrating a positive return on investment. References to a business case were removed and the maturity stage definitions were reworked to reflect increasing degrees of process consistency.

Modeling Assurance/Assessment. The INCOSE MBCM includes a capability titled *Modeling Assurance* that focuses on the Model Assurance Level construct that measures model maturity and adherence to best practices. The cited report was determined to be not available to the public, so it was replaced with an alternative citation. For NASA audiences, the assurance terminology strongly implies Mission Assurance or Quality Assurance, both disciplines that are very different from the intent here. The MBCA capability was renamed *Modeling Assessment* and is now defined as "the ability to assess a model and its impact to successful project execution." It does reference the Model Assurance Level approach, but it also introduces the concepts of model criticality, fidelity, and pedigree; these are all explored in NASA-STD-7009, *Standard for Models and Simulations* (2016).

Data Federation. The capability *Distributed Database/Tool Interoperability* was heavily focused on a federated data architecture. Federation is a possible solution to the challenge of interfacing a growing number of tools, but the team wanted to maintain a solution-neutral approach. It was reworked to focus on robust and effective tool interoperability.

MBCA Glossary. The MLT developed a short glossary specific to the NASA MBCA and made it available during the assessment. This defined several obscure terms which assessment participants may not have immediately understood, such as *digital artifact* or *structured data*. It was also used to specify which of several meanings commonly in use were intended; this was especially useful for loaded terms like *digital twin* and *digital thread*.

MBCA FAQ. The MLT also developed a frequently asked questions (FAQ) list for the MBCA. This was used to add additional clarifications too verbose for the matrix and offered explanations in more common language. It also attempted to assuage the fears some stakeholders had in participating – for examples, about possible consequences to being too low or too high on a maturity stage.

INCOSE MBCM Improvements

INCOSE should consider making corrections based on the findings documented above regarding re-categorization, clarifications, and editorial corrections. Special attention should also be given to the following:

Systems Engineering Emphasis. More emphasis should be placed on systems engineering by breaking down *SE Technical Processes* into separate capabilities. Except for *Verification & Validation* and *Stakeholder Requirements*, the core lifecycle processes are grouped together into a single capability. This imprecision does not reflect the diverse applications of MBSE to system developments.

Non-MBSE Concepts. Remove all requirements for specific non-MBSE concepts. Two examples of this are the Knowledge, Skills, and Ability (KSA) construct and continuous technical reviews. KSAs are required by the matrix to mature in three of the capabilities in the *Workforce/Culture* category. The intent of defining and understand what our personnel need to know and be capable of is vital to any MBSE effort, but KSAs are just one of several solutions. The *Model Based Reviews* capability requires the practice of a rolling or continuous review approach, in contrast to milestone reviews, to achieve Stage 4 maturity. While this is an exciting prospect and would be of benefit for many system developments, the goal of organizations using the MBCM should be to enable that ability, not forcing that specific practice. Likewise, maturity ratings should focus on that ability, but ratings should not be held back because teams decide it is best for them to continue to hold milestone reviews.

Maturity Stage-Capability Alignment. Ensure alignment of maturity stage definitions with their associated capability. The *Model-Related Training* capability becomes experienced based after Stage 1. This is redundant with the user and modeler skills gauged elsewhere, and it leaves a gap in the development and delivery of advanced MBSE curriculum. The capability *SE-Driven Model Plan*, after Stage 0, becomes driven by model scope instead of the quality of the MBSE plan. *Modeling Integration*, which the authors take to be an assessment of how well model elements are related to each other, begins with element relationships at Stage 0, but pivots towards methods and element reuse (which are both covered elsewhere in the MBCM).

Conclusions

As NASA continues its journey into the digital future, it will be imperative to have relevant and actionable metrics. As a NASA administrator once said, “If you can’t measure it, you can’t manage it.” Good metrics enable a determination of what level one has achieved and what that enables. Furthermore, it provides context for both “how far we have come” as well as “how far we have to go”. The INCOSE MBCM as tailored by NASA offers this – a clear set of actionable metrics. The lightweight approaches utilized proved to be effective and efficient ways of achieving near-complete consensus. At NASA, with ten Centers and twelve opinions on every topic, this is a fantastic result.

By utilizing these metrics across our NASA centers, we provide background and context for digital transformation initiatives. This provides clarity to stakeholders that nothing has been forgotten (e.g., training, security, deployment) and thus enable buy-in. There has been an observed reduction in resistance to change when it proceeds systematically according to planned levels. It is valuable to know where one is, absolutely and relative to the Agency. The ability to do systematic transformation planning is a major consequence of utilizing the MBCA. In digital transformation, there are always pockets of significant progress that is lost in the depths of an organization. We have been able to identify and leverage various vanguards at various centers, which enables sharing and communication between advanced teams further accelerating the transformation.

The NASA MBCA has provided crucial structure to the digital transformation of systems engineering across the Agency, and it continues to guide the path of that transformation – ultimately enabling NASA's scientific, research, and exploration missions.

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Biography

Greg Pierce is the Digital Engineering and MBSE Lead for the Engineering Directorate at Johnson Space Center. He serves on NASA's MBSE Leadership team and leads NASA's MBCA activities. He also contributes to the leadership of the systems engineering discipline at JSC in several capacities, such as chairing the JSC Systems Engineering Working Group. Pierce is a career systems engineer with extensive experience in the development of flight systems such as space suits and jetpacks. Pierce, a long-time INCOSE CSEP, has a BS in aerospace engineering from the University of Michigan in Ann Arbor.

Patricia Nicoli received her BS in Electrical Engineering from the University of North Dakota and her MS in Industrial Engineering with a Systems Engineering Focus from the University of Florida. She is currently serving as the Chief for Technical Processes and Tools at Kennedy Space Center. She also serves as the Digital Engineering Systems Engineering Lead. As part of this function, she coordinates across the different NASA Centers with MBSE leaders and practitioners to increase the model-based capabilities of the workforce and migrate to data driven processes using modern applications and tools. The goal is to provide improved processes to enable the workforce to deliver quality products consistently and efficiently.

Terry Hill has been with NASA for over 25 years and serves as the Digital Engineering Program Manager led out of NASA Headquarters' Office of Chief Engineer. He is responsible for providing an executable strategic and implementation approach for delivering digital engineering, MBSE methodology and interoperable tool chains to usher the agency into the modern world of DE design and SE. He has a BS in aerospace engineering and an MS in aerospace guidance, navigation, and control theory from the University of Texas at Austin.

Dr. Steven Cornford is a Principal Engineer in the Strategic Systems Office at NASA/JPL/Caltech. He got a double major in Mathematics and Physics from UC Berkeley, an MS and a PhD in Physics from Texas A&M University. Since coming to JPL in 1992, he has been part of the conception, design, management. building and testing various spacecraft and their components. He has performed a variety of research with the goal of making things better, more practical, or more efficient. Lately he is a contributing part of NASA's Digital Transformation efforts. He has authored over 130 papers and been awarded the NASA Exceptional Service Medal among others. He was in a rock band which recorded two albums, and still plays music with his three wonderful boys and his wife.