34th Annual INCOSE international symposium

hybrid event

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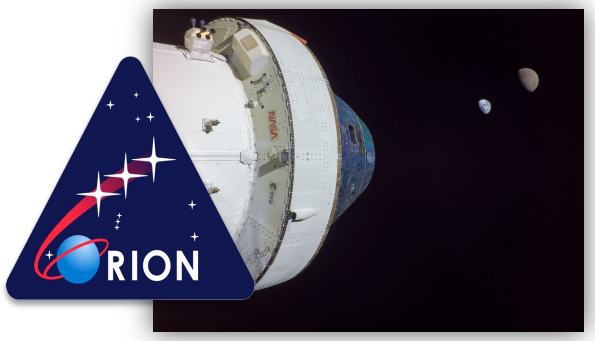
How the INCOSE Model-Based Capability Matrix Has Steered Model-Based Systems Engineering Transformation at NASA

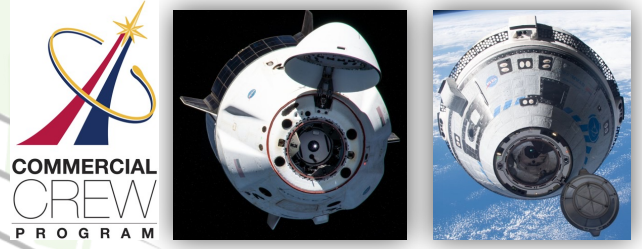
Gregory Pierce, Patricia Nicoli, Terry Hill, and Steven Cornford
National Aeronautics and Space Administration

Change at NASA – JSC's Perspective

20 years ago

Now





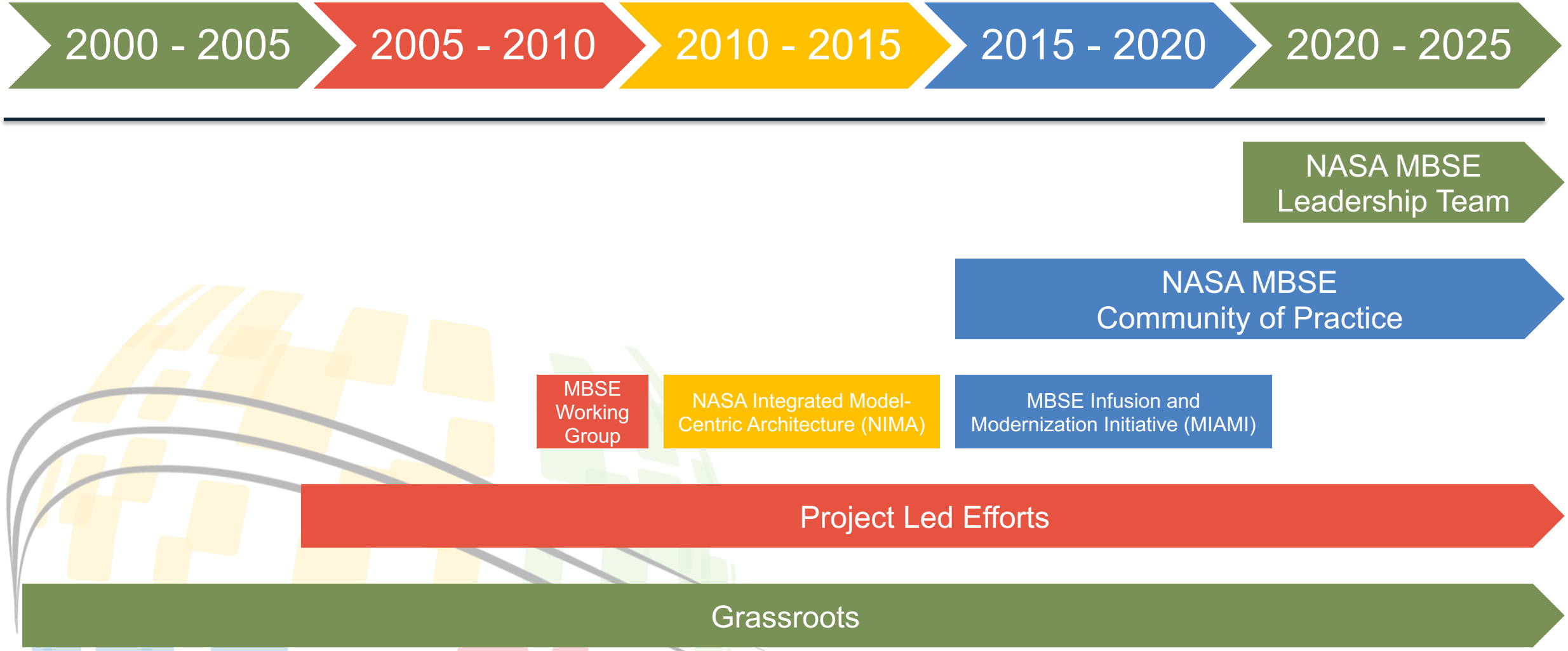
NASA's Digital Engineering Need

…from Concept to Operations

Historically a change of Presidential administration or Congress means a change to our missions/priorities/budgets

Improve how the Agency Engineering Domain operates over the entire NASA lifecycle by effectively managing complexity, reducing cost and schedule, and improving product integrity via the integration of processes, digital tools, and techniques along with seamless flow of information throughout the engineering system development life-cycle (concept development, design, testing and validation, manufacturing and operations).

Background – MBSE at NASA



Guidance & Navigation

At its formation in 2020, the NASA MBSE Leadership Team (MLT) recognized:

- The need to provide structure and direction to the myriad digital transformation activities at NASA.
- The need to understand the Agency's MBSE workforce maturity, processes, and tool usage.
- That the actionable metrics of the INCOSE MBCM, if tailored for NASA, could provide both.

What is the Matrix?

Tool to assist organizations assess the maturity of their model-based systems engineering (MBSE) capability, establish goals, and plan for further development

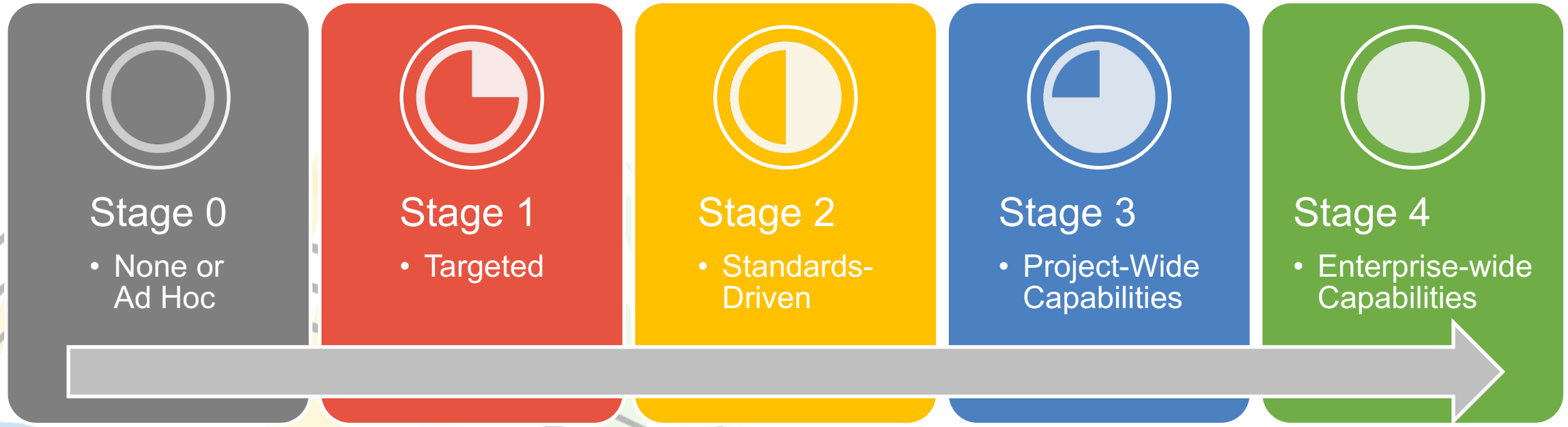
- INCOSE Model-Based Capabilities Matrix (MBCM) or Assessment (MBCA) (INCOSE-MBCM-2020-001.1)
- List of 42 model-based capabilities across 8 categories (INCOSE version)
- Defines 5 levels of maturity for each capability – Stage 0 -> Stage 4
- Provided User Guide has suggestions for use and tailoring

Category	Capability	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4
6. Modeling Tool Construction	Model Management	Model management is ad hoc.	Model management is an assigned role.	Model management adheres to a standard or to a defined approach.	Model management is applied to all models for a system.	Model management is applied to all models for an enterprise.

Capability Description
Model management is responsible for establishing policy and managing the oversight of model collection activities, model valuation, acquisition and strategic model loans, for ensuring the application.

Maturity Stages

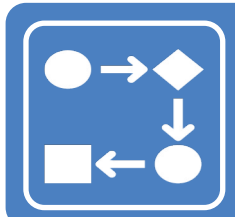
Increasing Stages of Capability generally defined as:



MBCA Categories

1. Workforce/Culture

- Training, Guidance, & Skills



2. SE Processes/ Methodology

- SE Aspects Modeled

3. Program/Project Processes Methodology

- Reviews, Metrics, & Plans

4. Model-Based Effectiveness

- Trust & Truth

5. IT Infrastructure

- Collaboration, Licensing, & Access

6. Modeling Tool Construction

- Function, Interoperability, & Independence

7. Model Use

- Extent and Quality of Use

8. Modeling Policy

- Governance, IP, & Innovation

Center vs. Vanguard Assessments

- Each NASA Center spans a broad range of MBSE maturity – a single score is not possible.
- Two center-level perspectives were assessed:
  1. NASA Center – the typical practice or the institutionally provided processes and infrastructure in place to support projects.
  2. Vanguard – where there is at least one project or organization operating at a higher maturity.
- Vanguard is an aggregate – different projects may be used for each capability.

This dual perspective allowed the honest capture of institutional maturity while also illuminating areas of advanced ability and practice, which represent opportunities for growth across the Agency

Assessment Results

Phase I

- Early 2021
- Proved viability and utility
- Quick assessment with small teams or individuals
- Provided initial guidance to MLT plans
- Identified ‘lift-and-shift’ opportunities

Phase I – Center Average 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

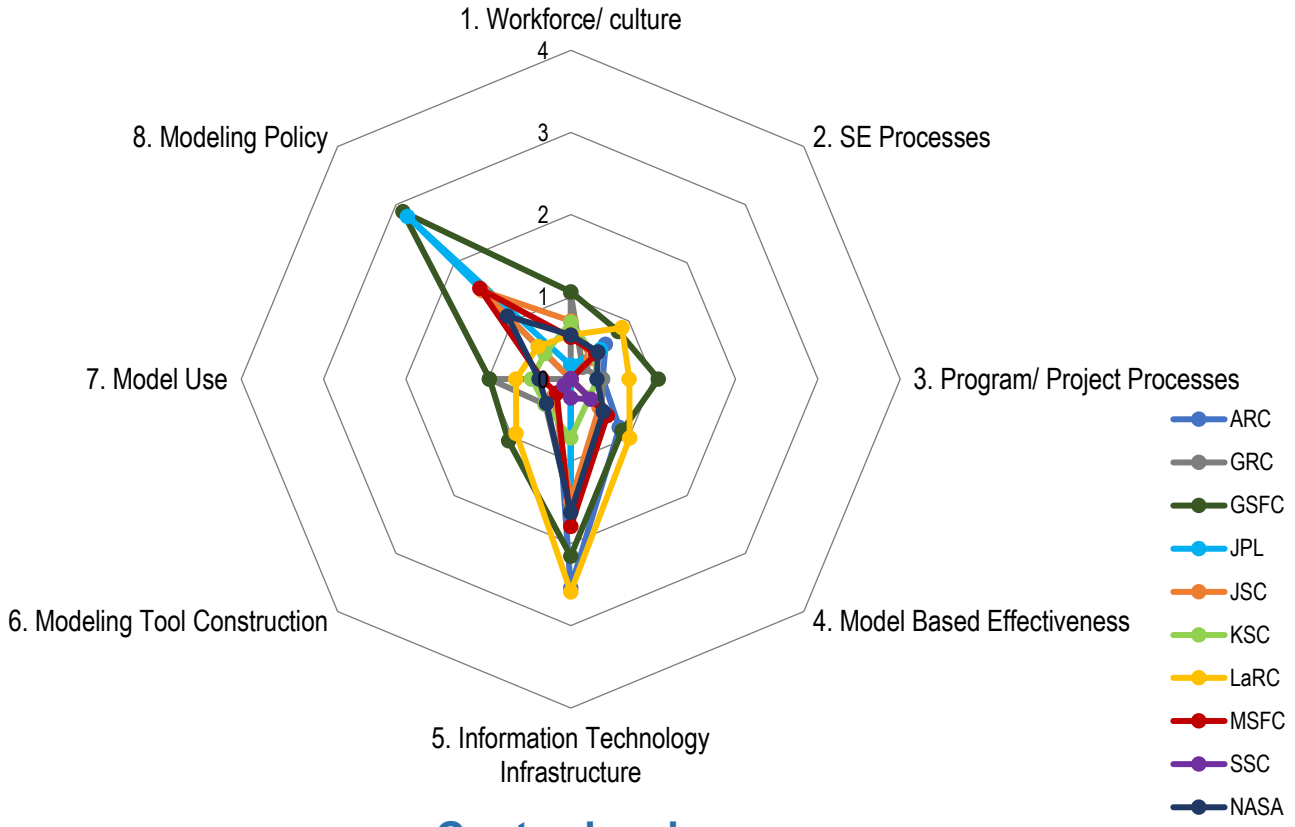
Phase II

- Mid 2021
- Refined and formalized assessment
- Validated Phase I results
- Found modest, and mostly ad hoc, institutional capabilities at NASA centers
- Identified expertise pockets and vanguard projects

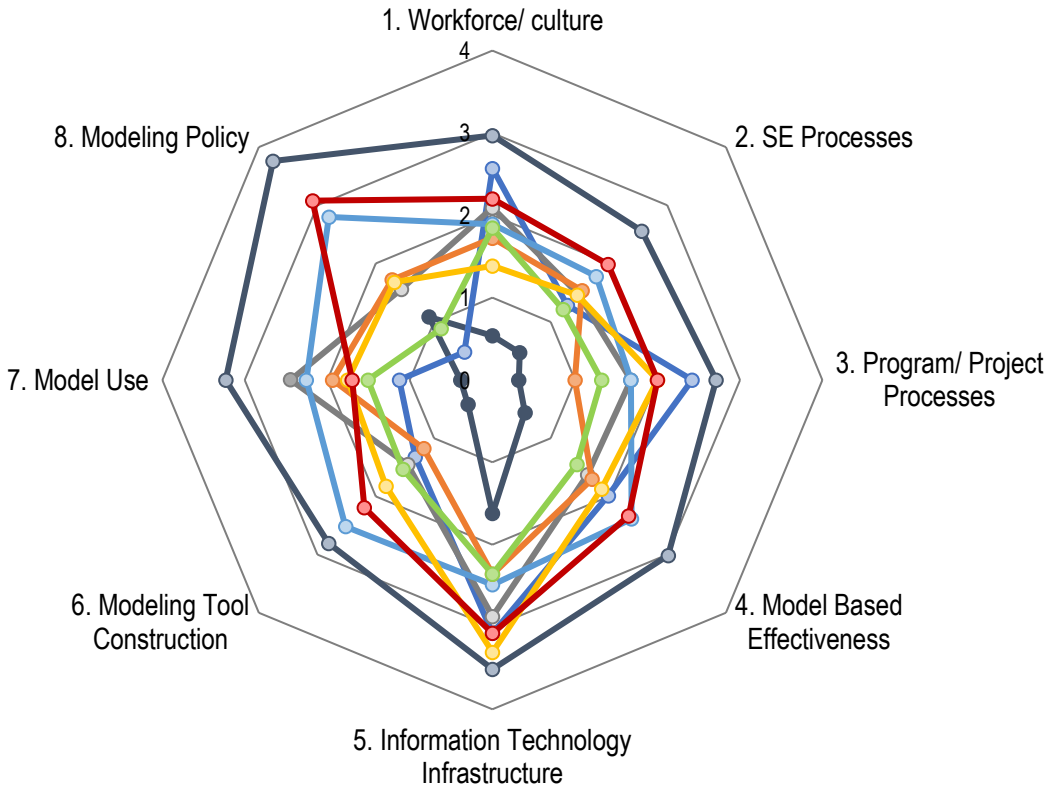
Phase II – Center Averages

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

Phase II – Center & Vanguard Averages



Center-level



Vanguards

Phase III

- Late 2023
- Update on progress and plans
- Used updated matrix
- Results show positive trend in maturity
- Large jump in ‘Center Max’ scores reflect the initial effects of the MLT’s work

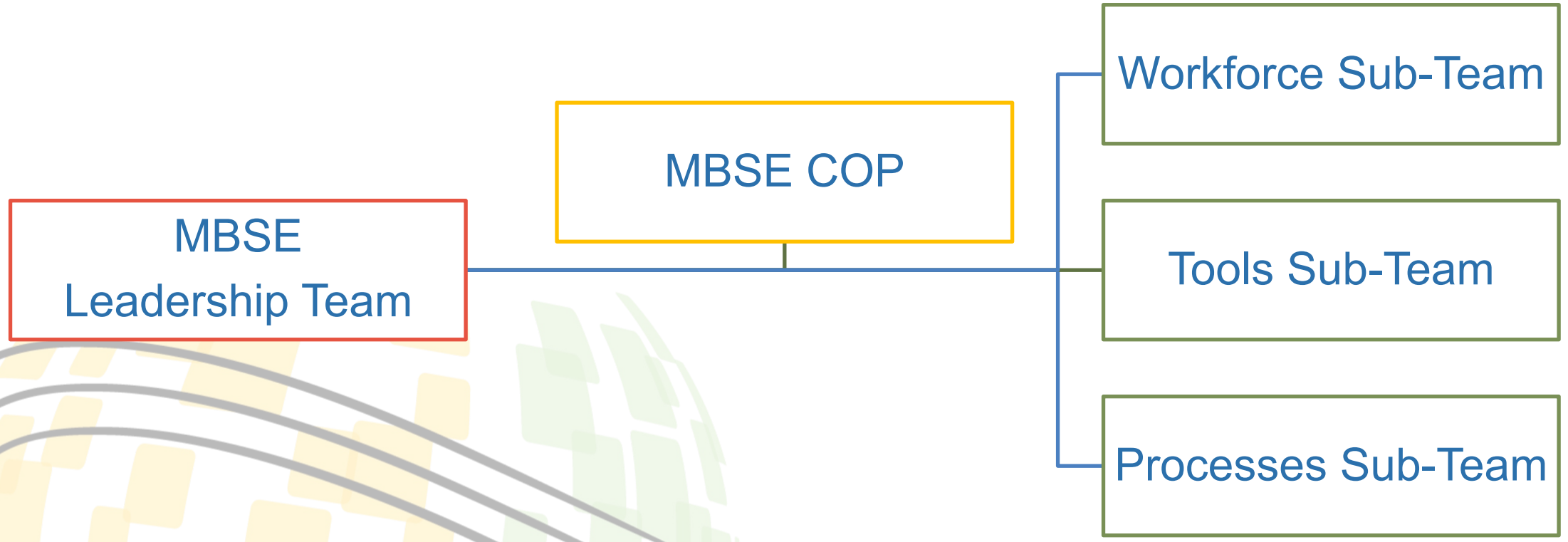
Comparison – 2021 to 2023

Phase III – Center Averages

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

MBCA-Driven Activities & Products

NASA MBSE Leadership Team & COP



Workforce

- Initial Focus
  - Training
  - Roles and responsibilities
  - Model development skills

Work-force/Culture from a NASA average of 0.5 to 1.0

- Benchmarking
  - Industry, government, and academia
  - MBSE use, modeling skills, modeling roles and responsibilities, and training practices
- Activities
  - Website that contains links to the available training material, videos, and courses
  - Definition of roles & 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.
- Future Work
  - Common terminology, MBSE usage and policies, and further refinement of training requirements.

Tools

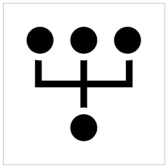
- Initial Focus
  - Digital thread and toolchains
  - Tool and their ability to integrate
  - IT security
  - Tool governance
- Benchmarking
  - Catalogued all software tools in use at NASA
  - Included how they are connected and used
- Activities:
  - Demonstration and evaluation of commonly used tools
  - Participating in defining common standards for data transformation that would increase tool and data interoperability

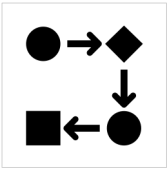
Modeling Tool Construction from a NASA average of 0.4 to 0.8

Processes

- Initial Focus
  - Program/Project Processes
  - Concept Development
  - Crosscutting SE
- Activities:
  - Digital Twin Pilot Project
  - INCOSE IS2023 Best Paper – Modeling & Simulation
    - Orion SysML Model, Digital Twin, and Lessons Learned for Artemis I.
  - Modeling of NASA Procedural Requirements Processes
  - INCOSE IS2024 Paper
    - Modeling NASA's Procedural Requirement Processes - Implications for Digital Future.
  - Lead MBSE CoP Work Topics

SE Processes from 0.4 and Program/Project Processes from 0.3 to a NASA average of 0.8

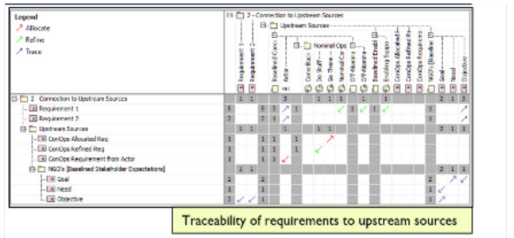




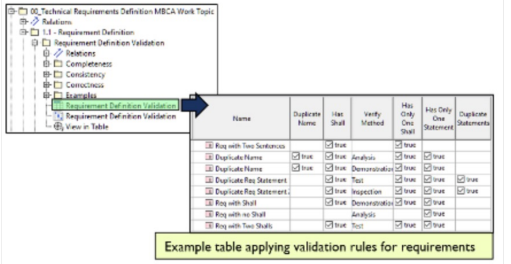
NASA MBSE CoP MBCA Work Topics

- Technical Requirements Definition
  - Shared and compiled examples
  - Generated templates and sample artifacts
  - Wiki guides were revamped
- Configuration Management (of Models)
  - Produced new examples and instructional materials
  - Reworked CM portion of NASA's modeling plan template
- Stakeholder Expectations
  - Vanguard projects shared experiences and best practices
  - Created/updated reference material
  - Broadened use of model-based export reports
- Planned:
  - Verification & Validation
  - Interface Management
  - Logical Decomposition
  - Design Solution Definition

Requirement Definition Process Traceability and Validation

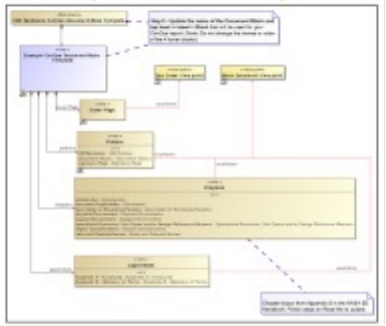


Traceability of requirements to upstream sources



Example table applying validation rules for requirements

Concept of Operations Report Model



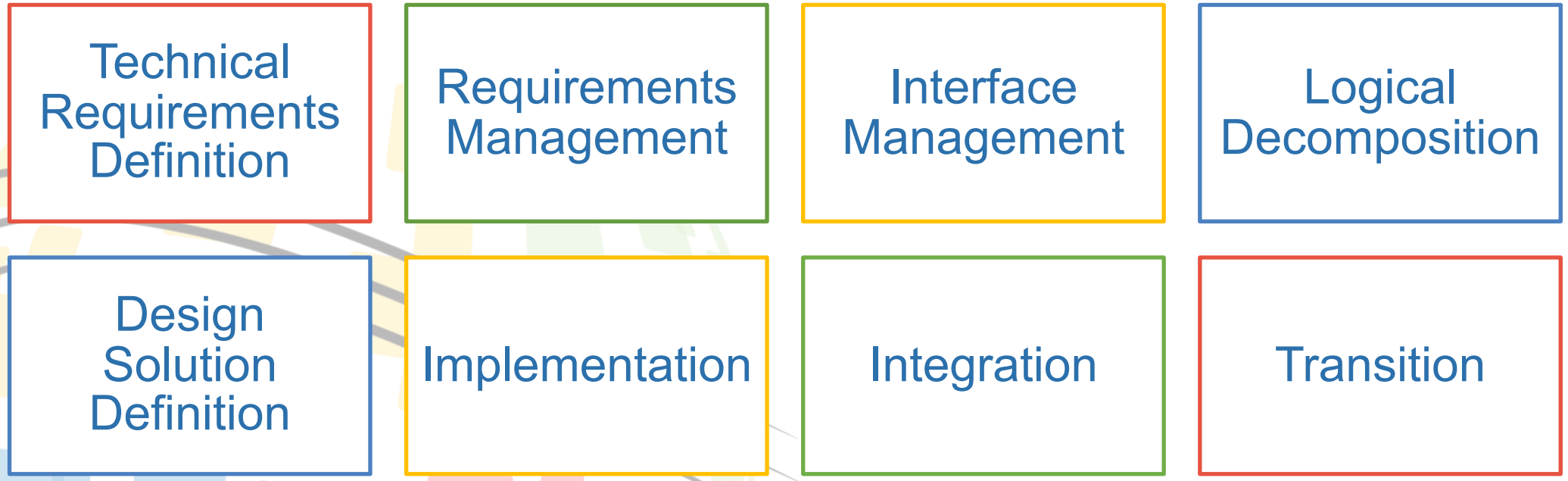
Tailoring & Modifications

NASA Tailoring Strategy

- Maintain intent of each capability
  - Goal is to leverage the tool's pedigree as an industry standard
- Reflect the NASA Systems Engineering "Engine"
  - Change references from IEEE 15288 to SP-6105
- Put more emphasis on the SE
  - Break down "SE Technical Processes" (processes on the "V") into separate capabilities
- Consistent capability definitions
  - Translated for NASA audience
- Re-categorized some capabilities to maintain more consistent themes
- Remove irrelevant factors
  - Knowledge, Skills, Ability development framework for training
  - Continuous technical review
- Editorial improvements
  - Corrected typos
  - Removed broken links
  - Terminology – Methods -> Methodology and removed Architecture Frameworks from Languages

SE Emphasis

- SE Technical Processes replaced by eight separate capabilities
- Allows for each facet to be addressed separately
- Reflects the diversity with which MBSE is applied



Collaboration Capabilities

- Collaboration Capabilities –
  - How teams exchange information and contribute to work products
  - Stage 0 – E-mails
  - Stage 4 – On-line, real-time collaboration amongst enterprise teams
  - Omits prevailing modeling practice in the use on-line model repository system.
  - Change: 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.

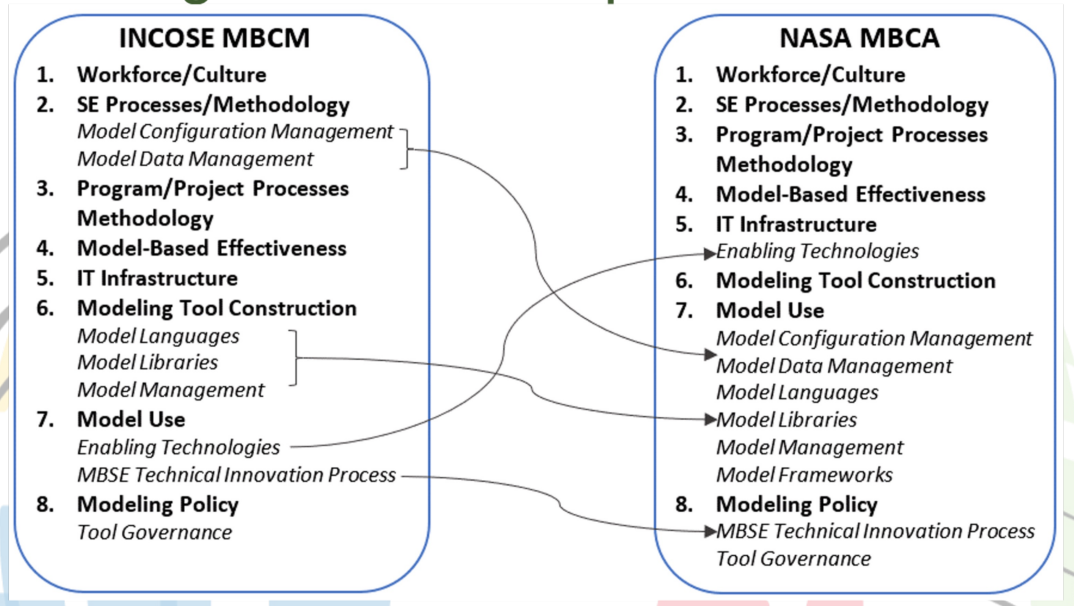
Model Frameworks

- INCOSE MBCM does not have 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 new Model Frameworks capability was added to Category 7, Model Use.
  - Addresses the need for a standardized set of model viewpoints (or view specifications) to be developed to meet stakeholder needs.
  - Ad hoc views at Stage 0 and matures to a standard framework that is tailored and used across the enterprise at Stage 4.

Re-Categorization

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.

Re-Categorization of Capabilities



- Category 2, SE Processes 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.

2023 Clarifications

- Deconflicted *Organizations* and *Enterprise*
- Reworked *Common Terminology* to distinguish ‘top tier’ definitions from shared glossaries and clarified ‘precedence’ vs ‘provenance’.
- *Use Strategy* was streamlined by removing business tool integrations.
- All *Systems Engineering Processes* were reworked for clarity and consistency.
- ‘Business Case’ references were removed.
- Reworked *Modeling Assurance* to be *Modeling Assessment.*
- Reworked *Interoperability* to be solution-neutral regarding data federation.
- MBCA Glossary and FAQ were developed and shared along with the Phase III review.

Areas for INCOSE MBCM to Improve

- Systems Engineering Emphasis
  - Split 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, such as the Knowledge, Skills, and Ability (KSA) construct and continuous technical reviews.
  - They are each just one of several solutions.

- Maturity Stage-Capability Alignment.
  - Ensure alignment of maturity stage definitions with their associated capability. For example:
  - The capability SE-Driven Model Plan, after Stage 0, becomes driven by model scope instead of the quality of the MBSE plan.

Lessons Learned

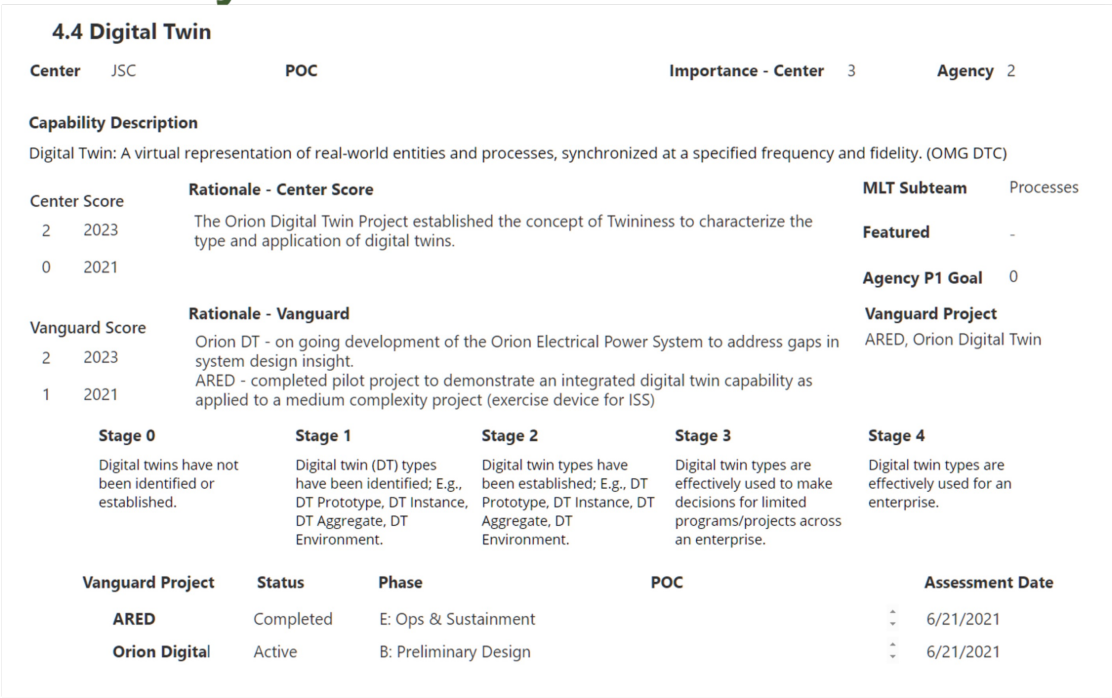
Assessment Approaches

- Expert Assessment & Community Review
  - An individual or small group performs detailed assessment
  - Stakeholders review
  - Lightweight way to reach consensus
- Panel Assessment
  - Moderately-sized group of representatives
  - Several working sessions were required
  - Requires significantly more time, but stimulates valuable discussion
- Vanguard Project Assessment
  - Most centers performed the vanguard assessment at the center-level
  - Some centers assessed the full matrix for each vanguard project

Collaboration Environment

- SharePoint lists were used to manage inputs since Phase II
  - Inputs were manually compiled via spreadsheets in Phase I
- Custom data entry form aggregated information
- Included guidance materials and results dashboards

Data Entry Form



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
2 2023
0 2021

Rationale - Center Score

The Orion Digital Twin Project established the concept of Twininess to characterize the type and application of digital twins.

MLT Subteam Processes

Featured -

Agency P1 Goal 0

Vanguard Score
2 2023
1 2021

Rationale - Vanguard

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)

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

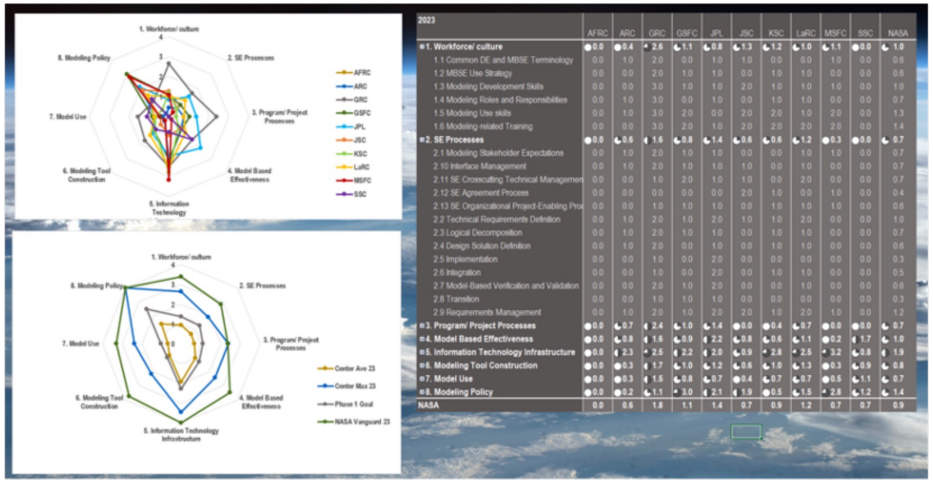
Analysis Techniques

- Weighted averages
  - Using an Importance factor, was helpful to gauge overall status for each center and capability
- Measures
  - Averages of each category, center, and NASA overall, maximums, deltas, and deviations
- Visualizations
  - Limited to views that could be autonomously updatable
  - Radar plots useful for quick impressions and seeing outliers
  - Bar charts are more useful for detailed inspection
  - Heatmaps and ‘pie slices’ were both useful in different situations

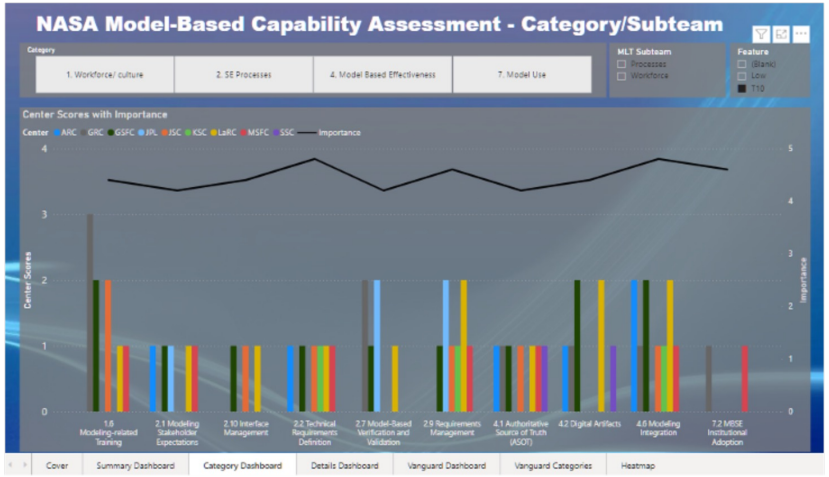
Data Integration and Analysis

- Excel (and alternately PowerBI) linked to SharePoint via Power Query
- Power Pivot used for derived columns, calculated measures, and table relationships
- Resultant data model used for all pivot tables and charts

Excel Report Workbook – Phase III Summary



PowerBI Dashboard – Phase II Top 10



NASA MBCA Findings

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.
- It provides context for:
  - How far we have come
  - How far we have to go
- The lightweight approaches utilized proved to be effective and efficient ways of achieving near-complete consensus.

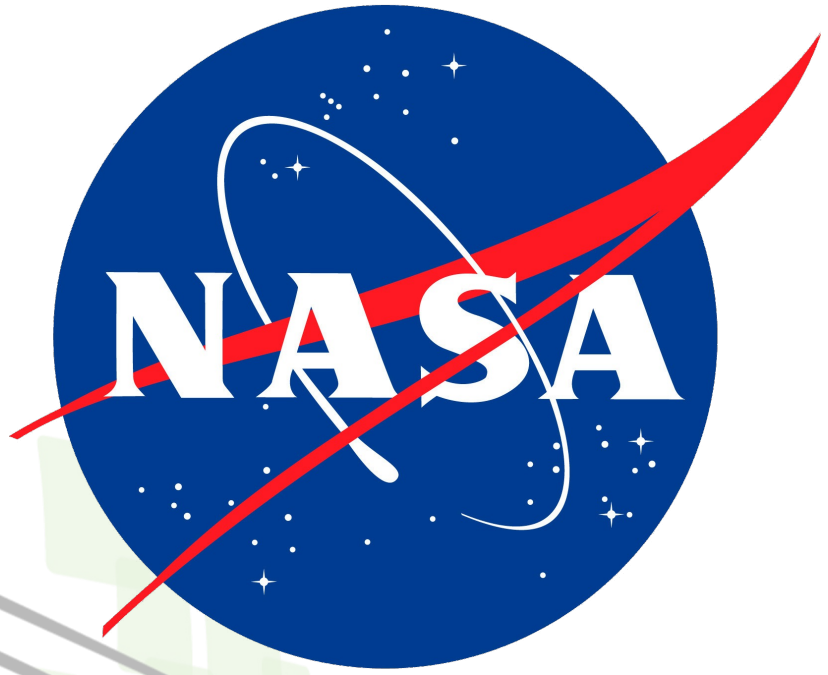
NASA MBCA Summary

The NASA MBCA provides:

- Background and context for digital transformation initiatives.
- Clarity to stakeholders that nothing has been forgotten and thus enable buy-in.
- Reduction in resistance to change when it proceeds systematically according to planned levels.
- Awareness of where one is, absolutely and relative to the Agency.
- The ability to do systematic transformation planning.
- The ability to illuminate pockets of excellence.
- For sharing and communication between advanced teams further accelerating the transformation.

The MBCA has provided crucial structure to the digital transformation of systems engineering across the Agency.

Questions?



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