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NASA's Use of MBSE and SysML Modeling to Architect the Future of Human Exploration

Terry R. Hill
NASA's Office of Chief Engineer/HQ
2101 NASA Parkway, Houston, TX 77546
281-483-8135
terry.hill-1@nasa.gov

Alanna E. Carnevale
The Aerospace Corporation
2011 Crystal Dr, Arlington, VA 22202
alanna.e.carnevale@nasa.gov

Audrey Morris-Eckart
NASA JSC Engineering
Project Management and Systems Engineering Division
2101 NASA Parkway, Houston, TX 77546
audrey.j.morris-eckart@nasa.gov

Vinodini Sundaram
Booz Allen Hamilton
2250 E Imperial Hwy
El Segundo, CA 90250
vinodini.sundaram@nasa.gov

Leon Z. Farhaj
Jacobs Solutions Inc.
2224 Bay Area Blvd, Houston, TX 77058
971-285-6274
leon.z.farhaj@nasa.gov

Abstract. One of the key roles of National Aeronautics and Space Administration (NASA) is to help mitigate the risk and lower expenses associated with space exploration, science, and discovery to the point where industry and international partners are willing and able to profitably take on larger, more complex missions. To do this, the Agency must undertake a transformation to a more modern integrated Digital Engineering approach to mission definition and planning. This paper highlights NASA's journey in understanding what this Digital Engineering Transformation means for the Agency, the benefits of this transformation to human exploration definition and planning, and the benefits to the current Artemis campaign engineering capability portfolio.

Keywords. NASA, digital engineering, exploration mission planning, Moon to Mars, Artemis, complexity management, MBSE, SysML modeling

Introduction

One of the key roles of NASA is to help mitigate the risk and lower expenses associated with space exploration, science, and discovery to the point where industry is willing and able to profitably take on these missions. Given the complexity of these types of missions coupled with flat or decreasing budgets there is a driving need to go from concept to operations in less time at reduced cost while dealing with societal expectations of risk aversion. NASA cannot achieve these goals using the planning, engineering, and operational approaches of the past. New ways of integrating, managing, sharing, and leveraging data and information is needed. This paper highlights how NASA is undertaking a transformation to modern integrated Digital Engineering (DE) including Model-Based Systems Engineering (MBSE) and associated models to link work groups from Headquarters to Programs to engineering teams at the field Centers to enable mission feasibility, planning, and operations enabling feasible approaches to taking humanity to the Moon and on to Mars.

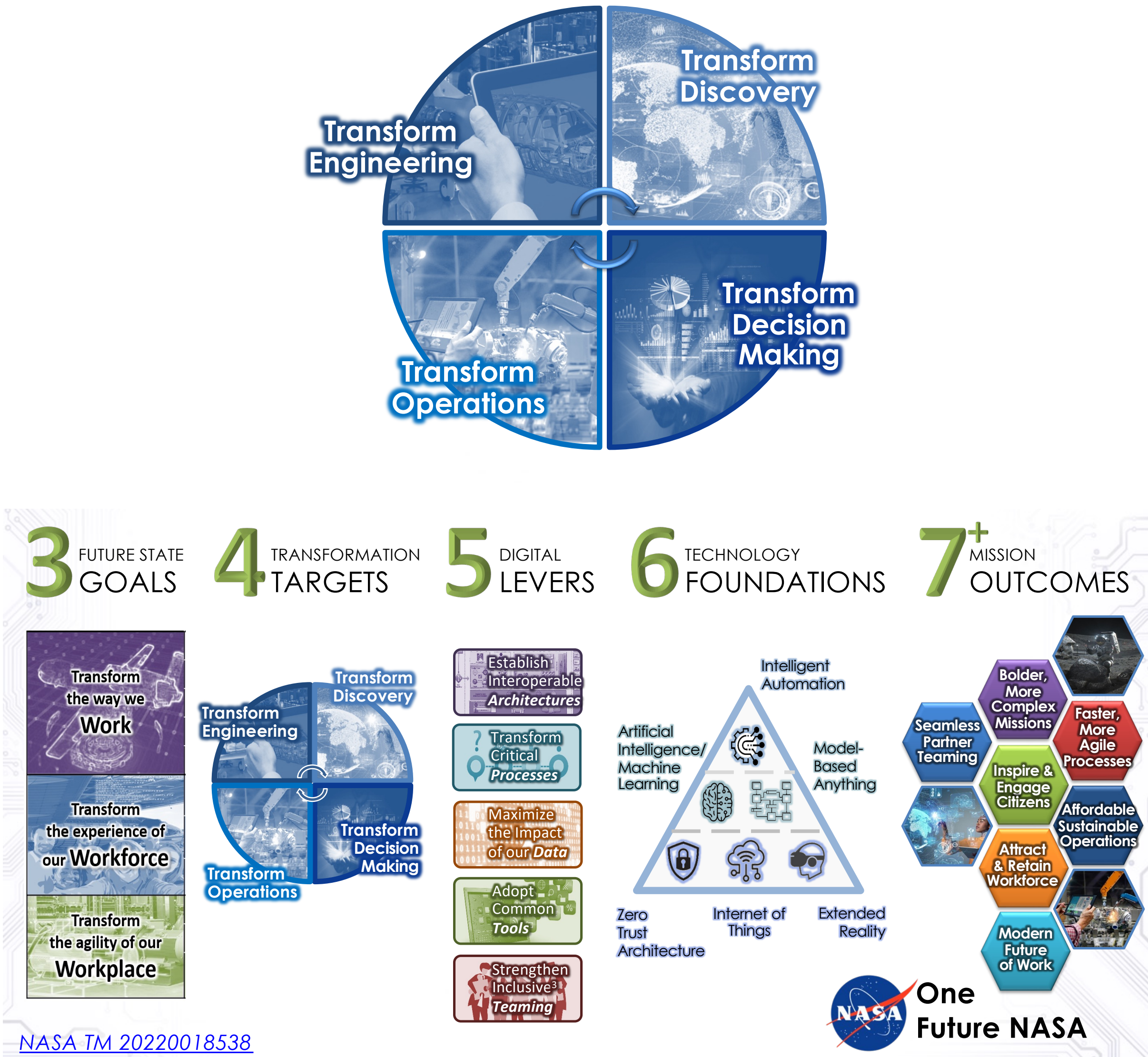

Figure 1. The four NASA Digital Transformation quadrants of focus and the NASA digital levers (NASA, 2022).

In alignment with INCOSE Vision 2035 (INCOSE, 2021), NASA's Digital Engineering Transformation (DET) strategy is built upon the larger NASA Digital Transformation (DT) vision, with three main goals: transforming the way work is undertaken, leveraging the experience of the workforce, and increasing the agility of the Agency. The Agency DT has been divided into four quadrants (Figure 1), one of which is the Engineering domain, and uses five main levers, and six foundations of focus: artificial intelligence (AI), process transformation, use of models, digital culture and workforce, collaboration, and data and analytics. (NASA, Dec. 2022) A major focus of NASA's DET, is for organizations to move from a primarily document-centric practice to a data-centric practice of Engineering as well increase the use of language-based models as part of the Systems Engineering (SE) technical processes.

NASA's Digital Engineering Need statement:

> Improve how the Agency Engineering Domain operates over the Program 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 system lifecycle (concept development, design, manufacturing, verification, validation, operations, and disposal).

For NASA and our industry and international partners to take on larger, more complex missions on Earth or beyond, the Agency must undertake a transformation to modern, integrated DE including MBSE. Therefore, once again NASA is setting its vision on more challenging goals which can only be enabled with the capabilities provided by modern SE methodologies and data-centric management of information.

Moon to Mars

NASA is leading a global, innovative, and sustainable space exploration organization with domestic and international partners with the goal of returning humanity to the Moon, achieve long-term surface presence, and continue on to Mars. The Moon to Mars (M2M) approach follows an objective-based strategy to focus on the "what" and "why" of NASA's strategic plans and is enabled by an integrated architecture comprised of contributions from multiple programs, projects, and systems to answer the "how". (NASA, Sep. 2022)

A process referred to as "architecting from the right" was established by NASA's Exploration Systems Development Mission Directorate (ESDMD) which takes high-level M2M driving goals and objectives and distills them down to specific architectural system elements. This approach begins with the end goals and objectives, determining the characteristics and needs necessary to satisfy the objectives, then defines the use cases and functions that would meet those characteristics and needs, and finally, ensures the proper elements, missions, and requirements are in place to accomplish those use cases and functions.

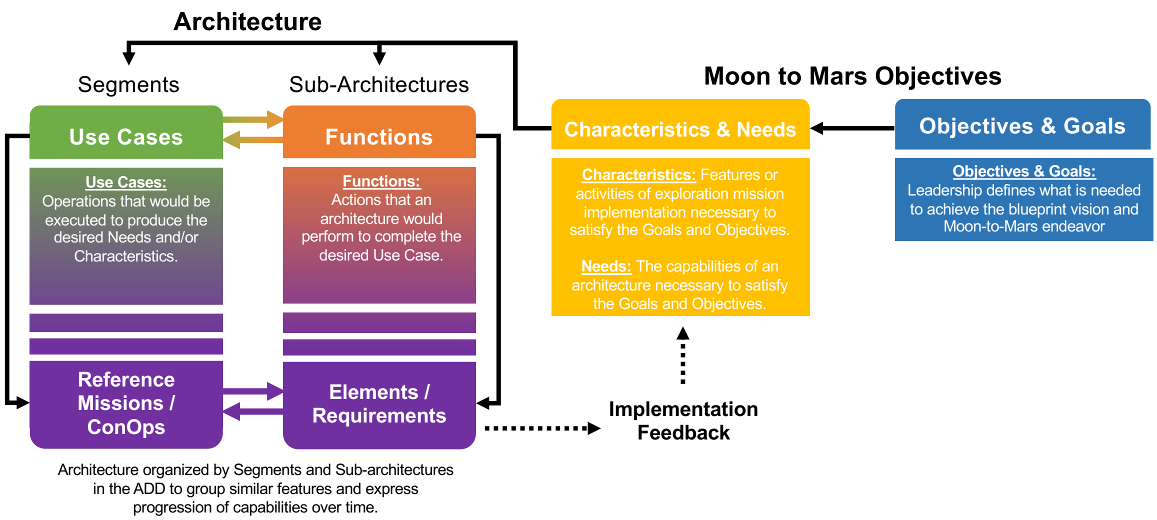

Figure 2. Architecting from the Right.

These components, the goals, objectives, characteristics and needs, functions, use cases, etc., can ultimately be considered architecture-related data and managed as such. The decomposition of objectives is just the beginning of a web of data that continues to grow as the architecture evolves and systems are defined. While this web grows, the data is also being updated annually to reflect the evolution of the architecture. This process is summarized in Figure 2.

Using the document-centric approach of the past, the architectural data would be stored and managed in multiple documents, including the M2M Objectives, Architecture Definition Document (ADD), requirements, Concept of Operations, and more. Documents are static and are maintained manually. They lack traceability, making it difficult to do a full analysis and assessment of any data, and changes to that data, contained within the documents. Version control on each piece of data, advanced user access permissions, and the detailed traceability between data cannot occur in static documents like traditional electronic documents, PDFs, diagrams, presentations, and spreadsheets. In addition, it is unclear how the data from one document is related and/or flows to data from another document, potentially managed by a different organization, program, or project team. Also, the data in these documents is often out of sync, inconsistent, and is often conflicting. There is no authoritative source of truth (ASoT).

This document-centric approach is no longer sufficient for managing the future set of complex data and information required for the increasingly complex missions NASA plans to undertake in the future. NASA's Exploration Systems Development Mission Directorate (ESDMD) is shifting to a data-centric approach enabled by MBSE methodologies to accommodate the aforementioned limitations. The result will be a data and information model of both the systems being developed as well as the various SE artifacts generated across their lifecycle. This data-centric approach allows for traceability, change impact assessment and updates when any data object is changed, ease of version control that allows for efficient and effective collaboration, reduced human error and overall risk, and ease of exportability and shareability of data and information. These approaches bring stakeholders together and enhances communication to ensure a common understanding of a system's architecture and associated activities.

ESDMD is using Systems Modeling Language (SysML) modeling tools with robust standards, compatibility, collaboration, capabilities, and configuration management features. Using this data-centric approach, an ASoT can be established and maintained within a single program. The next step was to develop a common language and framework to use as a translation device moving from a document-centric to data-centric approach. As shown in Figure 3, the metamodel below was established and is continuously iterated. With strong collaboration with other team members, the MBSE team has frequent discussions with the Architecture team helping to ensure stakeholders are speaking the same language, understanding relationships correctly, and working towards a common ontology.

Stakeholders that are unfamiliar with SysML modeling or MBSE approaches are unable to fully appreciate a comprehensive model without a simple, user-friendly way to review it, of which Cameo Collaborator for Teamwork Cloud provides this functionality. Cameo Collaborator is a client plugin that provides a web-based platform where the model can be presented to stakeholders, sponsors, customers, and engineering teams. Users can publish templates, navigate models, edit, comment, review, collaborate, and automatically circulate updates throughout the web-based and tool-based versions.

Tools like MagicDraw and Cameo Collaborator[1] are in use as part of the transition to a model-based approach of managing the architectural data, the next step is to ensure that the model is utilized effectively and is of value to the architecture and design teams and implementing programs and projects.

[1] Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

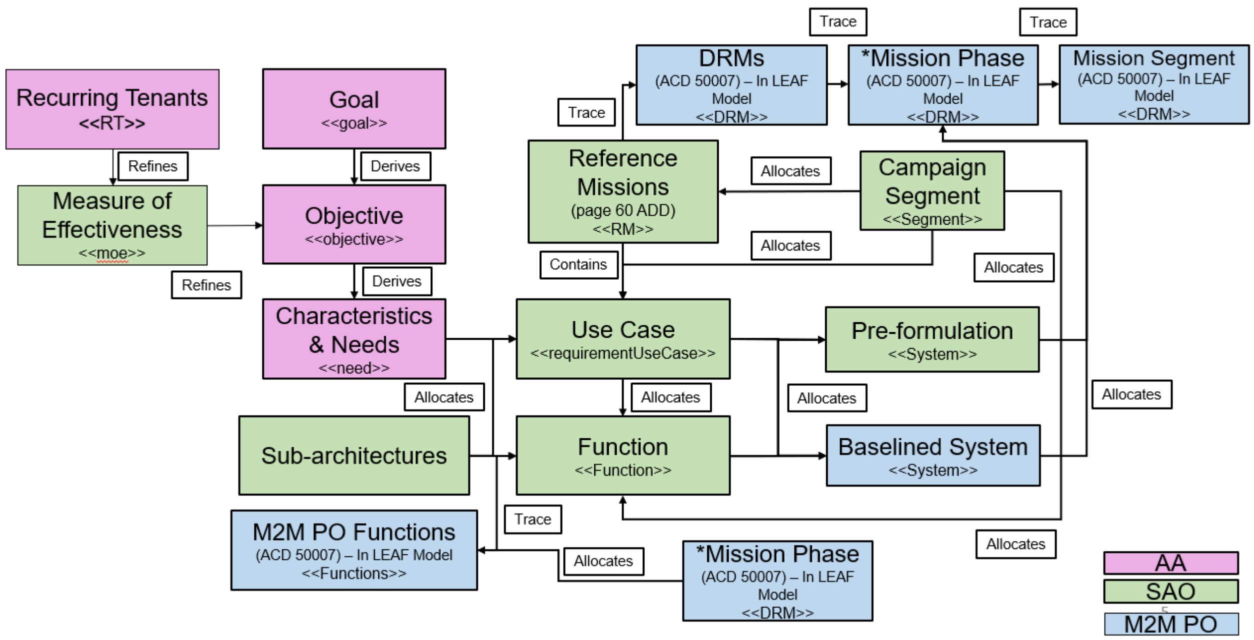

Figure 3. Metamodel Development to provide a notional common framework and ontology across multiple organizations and levels within NASA as part of human exploration.

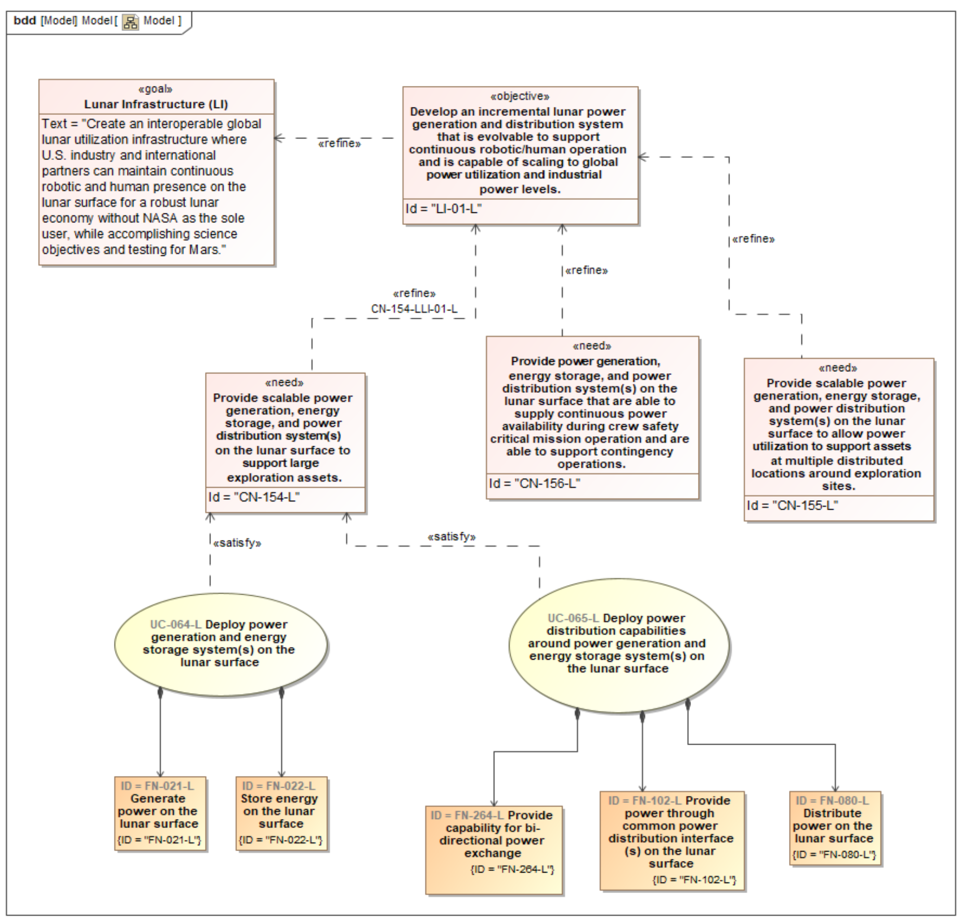

Figure 4. Example of Visual Diagrams.

There are numerous modeling use cases that allow for more effective integration and data analysis. The primary use cases focused on currently are high-level goals, objectives, needs, requirements and architecture traceability. By ingesting data into a SysML model, data and relationship identification can be quickly queried. Both direct and indirect relationships can be identified and analyzed. Visual products can be developed rapidly to enable review in a more straightforward method than looking solely at textual documents. An example is show below in Figure 4.

These data views can contain information that cross organizational lines of programmatic responsibility, showing how data flows from one group to another. In addition, these diagrams include features such as collapsible/expandible hierarchies, legends, and customizable layouts to make it easier for the user to navigate through and analyze the data.

Both direct and indirect relationships can be viewed through MagicDraw visuals. For example, if a user wants to see which objectives a system is indirectly related to, something called a "metachain" can query this information. Other questions this capability can help address include: For a given campaign segment, what are the functions and respective systems that have been defined? What are the systems allocated from specific functions?

Another modeling use case is an extension of the needs, requirements, and architecture traceability to understand how the architecture concept and associated needs and requirements are being implemented by Programs. Since many systems have been under development for much longer than the "architecting from the right" concept has been in place, it is important to not only ensure new systems are flowing from high level needs and requirements, but also that current systems can be traced back up to the higher-level needs and requirements of the Agency.

There is always the potential for inconsistencies and gaps within the data via traditional system engineering approaches; however, linking the data in a model format allows the requirement and architecture teams to better understand where the issues may lie. Since both the high-level Strategy and Architecture team as well as the Moon to Mars Program Office and Programs are storing data in a model, the data can be directly linked together with "project usages". This ultimately connects the flow of use cases and functions to needs, requirements, systems, lifecycle concepts, and other Program information. When pieces of data are updated in one project, that data automatically updates throughout both the project itself and the rest of the projects that "use" that project model (provided the teams update their usage). This means that if the Strategy and Architecture Office makes substantial updates to data such as the functions, the Moon to Mars Program Office will immediately be able to see the changes. This helps address the following questions: How does the implementation satisfy the strategy? How do the baselined systems and pre-formulation systems together accomplish the mission, goals, objectives, needs, and requirements?

Integration of the Artemis Campaign

The M2M Program Office (M2M PO) was established under ESDMD to support hardware development, mission integration, and risk management for the six Programs delivering critical hardware to the Artemis campaign: the Space Launch System (SLS) rocket, Orion spacecraft, Exploration Ground Systems (EGS), Human Landing System (HLS), Gateway Space Station, and Extravehicular Activity and Human Surface Mobility. This set of loosely-coupled Programs form a system of systems (SoS) which must be integrated together to deliver a tightly-coupled SoS architecture under the Campaign. Typical of many SoS architectures, the integration challenge of the Artemis Campaign is exacerbated by the physically distributed Program offices – between Johnson Space Center (JSC), Marshall Spaceflight Center (MSFC) and Kennedy Space Center (KSC) in addition to be contractually distributed as well. With NASA's strategic desire to remain lean and leverage industry partners whenever possible (providing hardware and services) with a variety in acquisition strategies employed for each system, the International Partners delivering systems and subsystems of the architecture. In this increasingly complex SoS environment, establishing collaboration and data integration strategies that are flexible and extensible for the length of the Artemis and Mars Campaigns is paramount for success.

The M2M Systems Engineering and Integration (SE&I) and select Program teams employ a data-centric approach using requirement management and modeling tools to support technical baseline integration. The MagicDraw and Teamwork Cloud (TWC) enterprise capabilities hosted by the NASA Office of Chief Engineer's DE Program Office is used across several teams within the Artemis Campaign which enables direct model collaboration.

The M2M PO team has developed the Lunar Exploration Architecture Framework (LEAF) which serves as the basis for the modeling development. LEAF is a SysML architecture model used to develop technical baseline modeling and assessment in support of SE&I processes. LEAF primarily consists of four tiers of data: physical, functional, mission, and requirements.

LEAF reflects the Artemis Campaign and Design Reference Mission (DRM) use case models, the functional baseline defining the capabilities required to execute the Artemis Campaign, the physical architecture and configuration baseline, and requirements traceability. LEAF supports SE&I processes and specific assessment activities: requirements definition and management, verification activities, validation activities, architecture change impacts, traceability gaps, and critical event analysis. These activities begin a part of the conceptual design phase and continue throughout development and later lifecycle phases. LEAF aims to enable data exposure and integration for a subset of vital systems engineering data to support SE&I activities.

A primary function of LEAF is to enable data integration across programmatic and even vendor/partner boundaries. For example, there is a need to provide strategic, objective, and mission need and requirement data to the Program teams to formulate traceability from system implementation up to strategic and science goals and objectives. Likewise, there is also a need to integrate system verification, validation, and test data to support an end-to-end design certification and qualification for a mission made up of a SoS.

Therefore, the team needed to establish a federated model approach whereby M2M/ESDMD can provide data to the Program teams and the Program teams can provide post-processed data to the M2M team. In defining the structure and process, the team took inspiration from a similar structure established by the Gateway Program to enable integration across the Gateway Digital Architecture (Crane, Morgenstern & Parrott, 2020). Figure 5 details the federated MagicDraw model structure used by the M2M team which is made up of MagicDraw native Project Usages, Tool APIs, and some custom connectors. At the top level of decomposition, the ESDMD team manages the high-level M2M driving goals and objectives, use cases, functions, and subsequent traceability.

The M2M team manages a model of enterprise-level needs and requirements, interface requirements, capabilities, etc. that the Program teams then ingest and link to. The result is a Federated Source of Truth (FSoT) for the Artemis Campaign SoS.

Note: For Programs like the Artemis Campaign *made up of a SoS, the concept "Federated Source of Truth" (FSoT) is used instead of ASoT. In this context, while each individual system of the SoS may have its own ASoT, there may be inconsistencies between systems. A FSoT enables the* Artemis Campaign *to ensure all systems have access to the same data and information, which helps to eliminate inconsistencies and errors that can arise when different systems use different data and information sources. With a FSoT, data and information are indexed, retrieved, and presented in a user interface layer where it is created and can be accessed by all stakeholders. This approach is used to ensure that the information used by different systems is consistent and current.*

At the lowest layer of this model structure, the LEAF ingests data from all Programs to support integrated assessments, impact assessments, gap identification, etc. This approach encourages but does not impose normalization across modeling teams. While the ideal scenario would be absolute consistency in modeling implementation, the federated approach recognizes the distributed nature of the M2M teams that make up the SoS, as well as the varied levels of maturity across modeling efforts, makes consistency difficult but not impossible.

As shown in Figure 5, the existing toolchain used by select M2M Programs natively integrate with the MagicDraw TWC environment – namely IBM's DOORS Next Gen is the requirements management tool of choice for three M2M Programs and has a built-in MagicDraw integration capability, Cameo DataHub. There are several other elements of the toolchain that is yet to be implemented, but the federated modeling environment with MBSE at its core has been a successful implementation by the M2M SE&I teams.

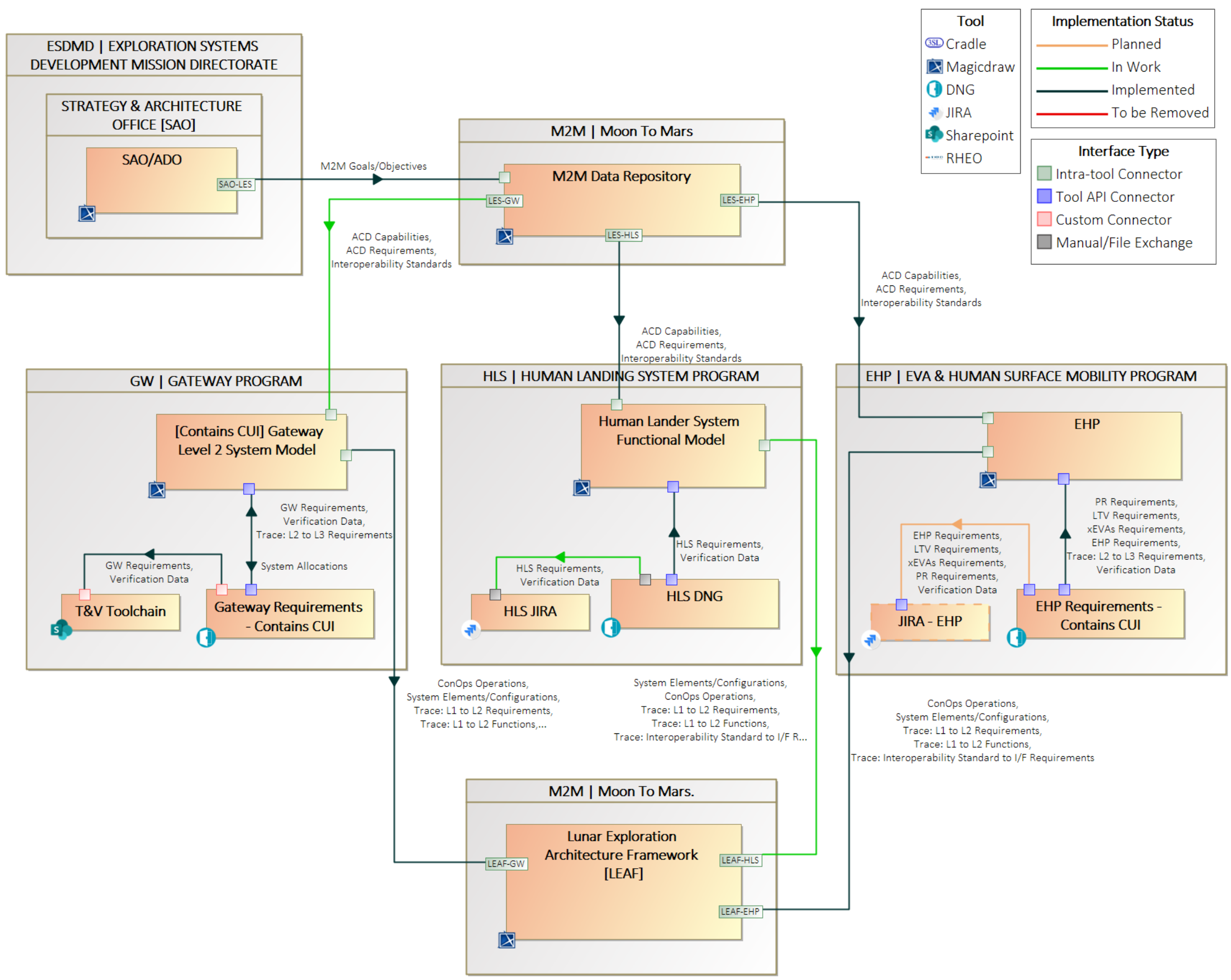

Figure 5. The existing and planned toolchain used by select M2M Programs natively integrate with the MagicDraw / TWC environment.

Integrated Modeling Environment

This integrated modeling environment was only possible through increased and intentional collaboration across siloed modeling teams through establishment of an Artemis Modeling Working Group (AMWG). This group meets monthly to discuss modeling issues/challenges, observe demonstrations of novel modeling techniques being executed across the teams, and identify opportunities for enhanced collaboration. As an output of the AMWG, the team has developed standardized modeling guidance for select use cases and standard process for repeated tasks like formulating traces across model boundaries.

Figure 6 details one such modeling guidance developed within the forum – a template and library for modeling logical and physical interfaces between docked/hatched systems, a use case that will arise for most all cross-Program interfaces within the Artemis Campaign.

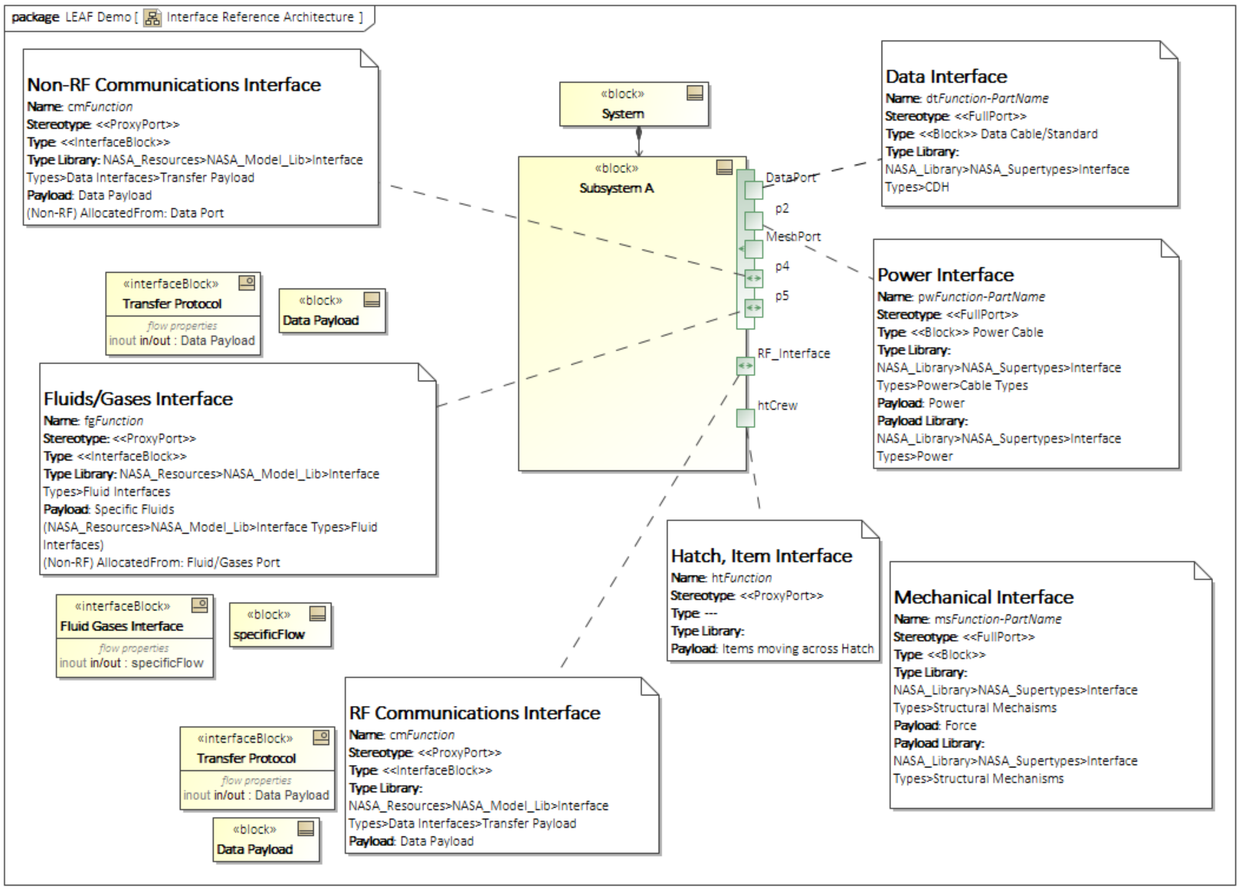

Figure 6. Interface Modeling Reference Architecture developed by AMWG.

With this integrated modeling environment in place, the M2M and Program teams have been able to implement and manage the following capabilities critical to establishing a FSoT for the Artemis Campaign:

Data Sharing/Access across Boundaries: Sharing of data, especially vendor procurement sensitive data, has posed a challenge for the M2M team. In order for the team to access to data and information from select Programs, data exchange requests must be submitted, and data is sent using traditional exchange formats (spreadsheet, pdf, document, etc.). Using the model interface, cross-Program data sharing is made more efficient and usable. The process of sharing data is also much less laborious on the part of the requester and the sender. Additionally, access control can be permanently managed with assurances that stakeholders will have access to current/up-to-date data enabling a FSoT. A similar concept is currently being explored across NASA program and vendor teams.

Development of Integrated Model Products: Some products generated from the LEAF include DRM models, Concept of Operations (ConOps) data, integrated system configurations and functional interface diagrams, and requirements traceability. Each of these products are implemented using this integrated modeling environment. For the Program teams to demonstrate how they are deriving requirements from the parent specification, all traceability and coordination is done in the model. Individual teams can bear responsibility for managing their technical baseline content, and all stakeholders can leverage data from other teams.

"Pulling" the Digital Thread: Once model data is adequately integrated, and a FSoT is established, the teams can then readily and easily pull the digital thread to automatically build the reporting packages and artifacts which were once stand-alone documents in which to inform decisions.

Mission Feasibility and Capability Portfolio Management

NASA's Lyndon B. Johnson Space Center (JSC) Engineering Directorate is primarily responsible for providing engineering support for human space flight programs and is made up of varying functional divisions based on expertise (e.g., propulsion and power, structures, avionics systems etc.). Each division includes many varied disciplines, types of work, programs supported, etc.—all of which need to be documented and managed to ensure the Directorate is working as intended to meet the needs of the Programs it supports (as described in NASA's DE Need Statement). The Directorate also provides subject matter expertise to industry and works in partnerships with academia to develop and fund space technologies to enable future space exploration endeavors. For effective management of the Directorate resources and identification of knowledge, functional gaps or facility needs, as well as look for new opportunities for exploration and outreach, knowing what the Directorate does, and who does it, is vital for managing the workforce.

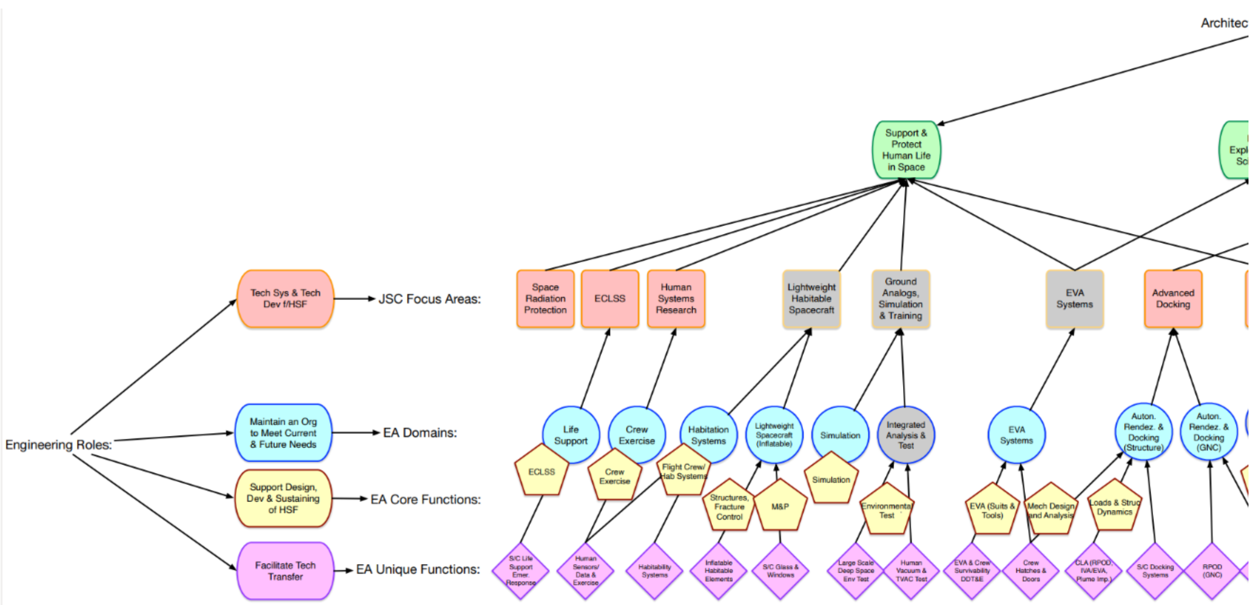

Figure 7. A representative portion of the larger, original Engineering Strategic Portfolio Map (too large to place in this paper) where the information was two dimensional and not able to be queried or exported for reporting.

To more effectively manage the strategic direction of the Engineering Directorate in support of human exploration, the Spacecraft Performance and Concept Engineering Branch was tasked to create and lead a steering group of technical leaders called the Advanced Concept Engineering Strategy (ACES) team. This group's charter includes ensuring alignment to mission goals and objectives and agency architecture as well as identifying gaps in technology development or capabilities to better coordinate resources. This information is key to successfully meeting the needs of the agency missions and programs and ensures that the

Agency is most effectively working on the correct advanced development projects. To be effective, ACES needs the capability to gather and manage this information with linkages to show traceability and gaps.

Often, this type of information is managed using a document-centric approach with basic tools such as spreadsheets, web-based lists, electronic documents or graphically via a strategy map (refer to Figure 7) which traces to a hierarchy of Center and Engineering domains, functions, focus areas, etc. This yielded typical problems associated with document-centric practices from which NASA's DET aims to transition from. Related documents had some overlap, resulting in repetitions and gaps in data, as well as inconsistencies as changes were made in only one document over time. Additionally, the drawing format does not allow changes to be made easily, is difficult to ensure updated information reaches all who need it, has unclear linkages and associated relationships between shapes, is limited in the amount and type of information which can be captured and managed, and is cumbersome for engineers and senior leadership to use.

A data-centric approach using models were used to address these concerns and create a new Strategy Map. Specifically, a SysML model was created to act as a deployable approach for senior leadership and engineers to interrogate for information all the while keeping the information linked to the SE&I framework of M2M and Artemis. It was able to include the information from the original strategy map, as well as new related information, such as points of contact, projects, partnerships, and agency goals.

The first information included in the model was the different engineering domains and functions. They were represented as elements in the model, which can have various properties as well as relationships to other elements. One example relationship is composition relationships to show a structural decomposition. Using this, the hierarchy of engineering domains and functions was made, which is shown in a Block Definition Diagrams (BDD), a snippet of which is shown in Figure 8.

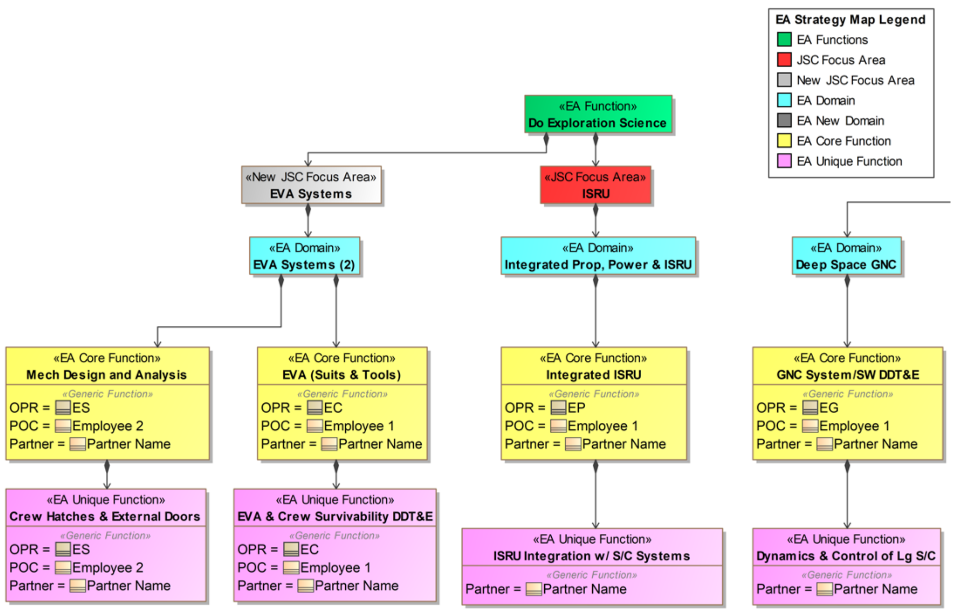

Figure 8. BDD in Strategy Map Model.

These elements also list their stereotypes at the top, as well as related information below, which was done by creating custom stereotypes that the elements can be applied as. This information is captured in profile diagrams. These stereotypes can have defined attributes that are of a specific type; for example, they may be a text or reference another model element. For example, Figure 9 shows a point of contact that has an associated phone and email stored as strings, and a division or organization that is a block (i.e., a model element).

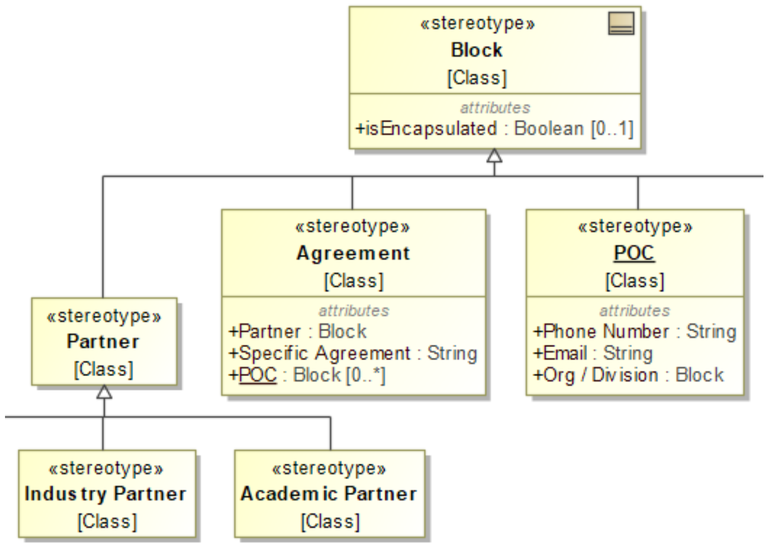

Figure 9. Profile Diagram in Strategy Map Model.

Another major type of information included was the Agency's M2M goals and objectives (NASA, Sep. 2022). As described before, there was already a modeling effort to capture this data. Fortunately, this effort can be used with MagicDraw's Project Usages, which allows reference to external projects. Specifically, in this case, all M2M goals and objectives can be brought into the Engineering Directorate Strategy Map model for tracing to Directorate functions, while still being managed externally. This means any updates or changes with the M2M goals and objectives will automatically be flowed into the Strategy Map model. The traceability between the two was made using Satisfy Relationships model functionality, which can be shown in diagrams like a Requirement Diagram or Dependency Matrix like shown in Figure 10.

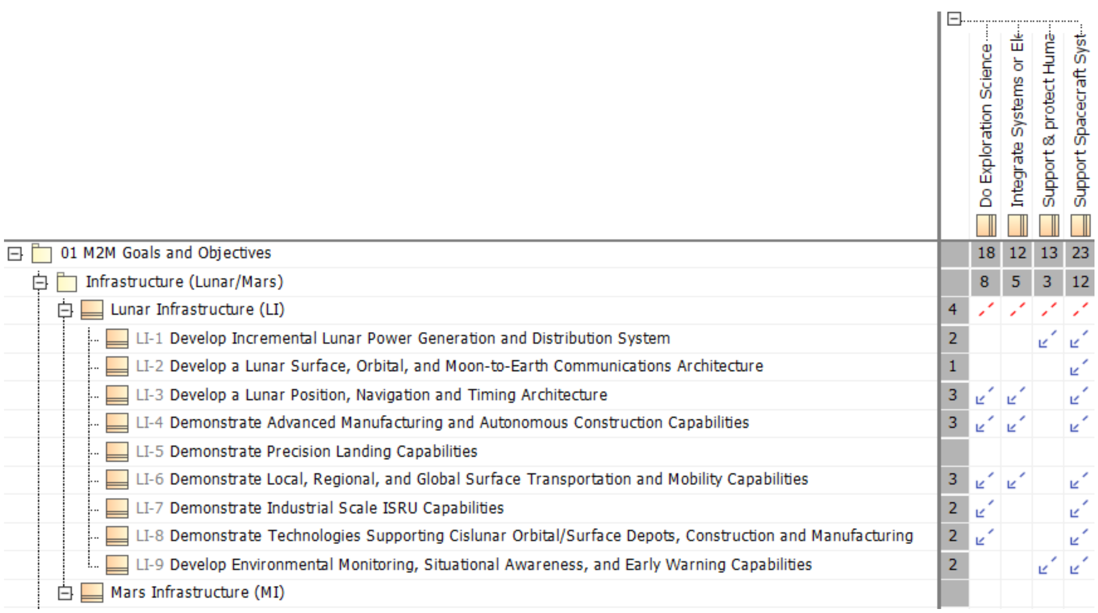

Figure 10. Dependency Matrix of Moon2Mars Goals to Directorate Domains.

With this base information, the next step was to provide capabilities for reviewing and updating the model. End-users should be able to make use of the model without being familiar with or having access to a modeling software, and there are three types of external reviewing of the model to support this: web-based platforms, report generation, and spreadsheet syncing.

Web-based platforms allow for the most user interaction with the model without a modeling application, as users can click through the various elements and diagrams on their browser; a screenshot of this for the Strategy Map model is shown in Figure 11. Additionally, some platforms enable model commenting and even some editing directly from the web version. These are examples of important types of interactive features, that through the web-based interface make it easily accessible and usable, requiring little to no training to start using it.

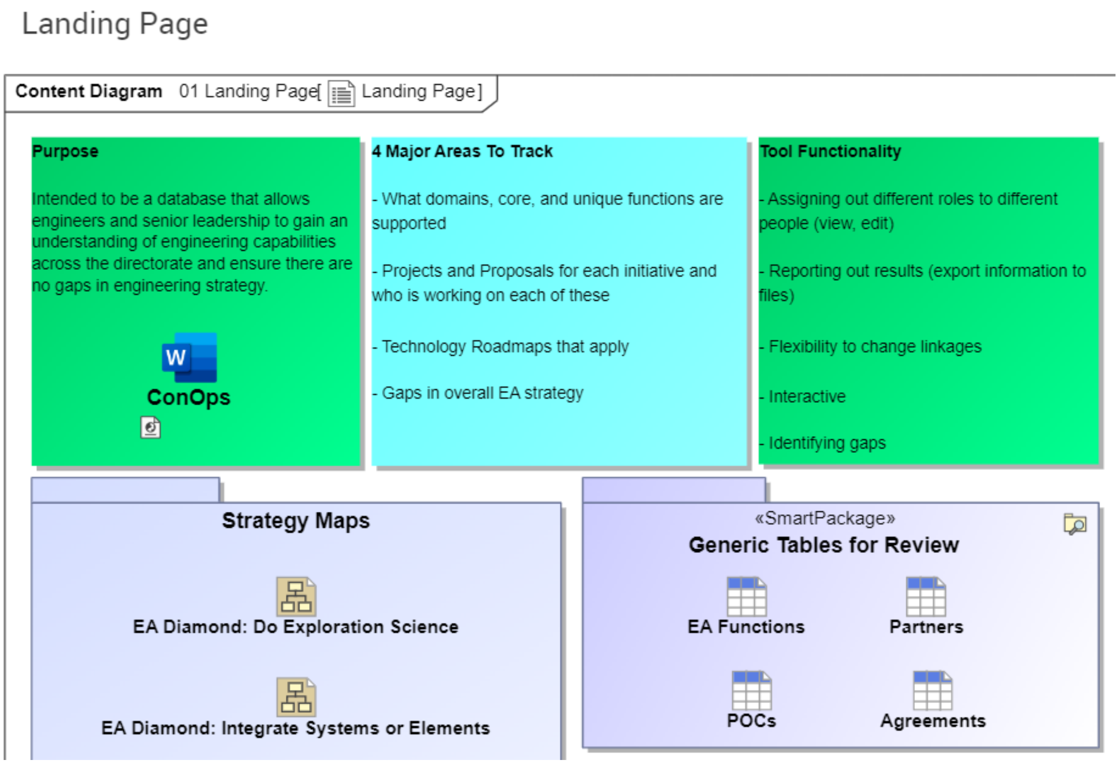

Figure 11. Cameo Collaborator Web Interface.

The second method of to support a project review is via report generation which is best for obtaining the information in the model in more traditional artifacts such as MS Word documents. Modeling applications may come with default templates for generating reports, but for more specific examples, templates can be made using Velocity Templating Language (VTL). An example template was made for various combinations of information in the Strategy Map model. With it, document reports can automatically be generated and updated with new information in the model. An example of a document VTL script can be seen in Figure 12.

Lastly, the model can work with spreadsheets to import and/or export information. For MagicDraw specifically, there are Excel/CSV Sync and Excel/CSV Import. Regarding the former, the Strategy Map model has Generic Tables in them that can be synced to an Excel File (Figure 13). Whenever there is a change in either the model or an associated spreadsheet, MagicDraw can either read from or write to the spreadsheet to capture the changes. It also should be noted that Generic Tables in SysML are fundamentally different than typical spreadsheets as the fields are not strings or values, but existing elements/properties in the model.

```
EA Core Functions in $diagram.name
#set($diagramElements = $report.getDiagramElements($diagram))
#set($supportHumanLife = $report.filterElement($diagramElements,
[$eaCoreFunction]))
#foreach($e in $supportHumanLife)
#       if($report.isEmpty($e.opr))
    1.  $e.name (NO OPR)
#       else
    2.  $e.name (OPR: $e.opr.name)
#       end
#end
EA Unique Functions in $diagram.name
#set($diagramElements = $report.getDiagramElements($diagram))
#set($doExplorationScience = $report.filterElement($diagramElements,
[$eaUniqueFunction]))
#foreach($e in $doExplorationScience)
    1.  $e.name
#       if($report.isEmpty($e.poc))
          • NO POC
#       else
#             foreach($poc in $e.poc)
#                   if($report.isEmpty($poc.phoneNumber))
          • POC: $poc.name (Number Not Listed)
#                   else
          • POC: $poc.name ($poc.phoneNumber)
#                   end
#             end
#       end
```

EA Core Functions in EA Diamond: Support and Protect Human Life in Space

1. Flight Crew/Hab Systems (OPR: EC)
2. Structures, Fracture Control (OPR: ES)
3. Mech Design and Analysis (OPR: ES)
4. Environmental Test (OPR: EC)
5. Simulation (2) (OPR: ER)
6. M&P (NO OPR)
7. Crew Exercise (2) (OPR: ER)
8. ECLSS (2) (OPR: EC)
9. EVA (Suits & Tools) (OPR: EC)
10. Dust Mitigation Expertise & Integration for Programs (OPR: EX)
11. Hazardous Testing (OPR: EP)

EA Unique Functions in EA Diamond: Do Exploration Science

1. RGD/Plumes
   - POC: Employee 1 (XXX-XXX-XXX)
2. EVA & Crew Survivability DDT&E
   - POC: Employee 1 (XXX-XXX-XXX)
3. Crew Hatches & External Doors
   - POC: Employee 2 (XXX-XXX-XXX)
4. Visiting Vehicle RPOD Ingreation
   - POC: Employee 1 (XXX-XXX-XXX)
   - POC: Employee 3 (Number Not Listed)
5. Onboard Autonomous Navigation
   - POC: Employee 1 (XXX-XXX-XXX)
6. S/C Docking Systems
   - POC: Employee 1 (XXX-XXX-XXX)
7. In-Space Robotic Assembly

Figure 12. VTL Template and Generated Report.

This means each part can be interacted with for more information (e.g., a point of contact, a function's owning domain, etc.) and any changes in the model—whether in the table or elsewhere will be updated everywhere else. Both document types support user access to data sets removing barriers to access as they are commonly utilized and easily shared.

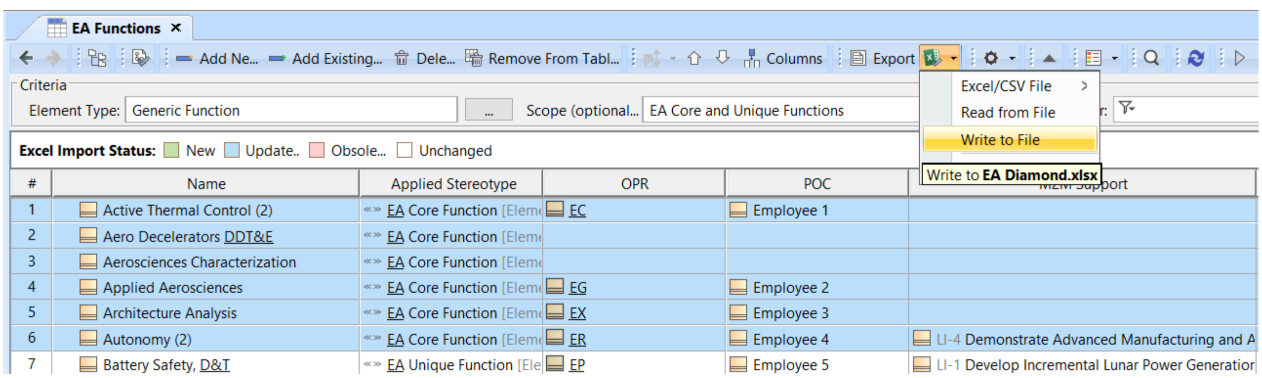

Figure 13. Generic Table Synced to Associated Spreadsheet

For larger reviews or information not directly managed in Generic Tables, the latter tool of Excel/CSV Import allows users to import information/corrections from a spreadsheet that will automatically be set up in the MagicDraw environment (i.e., as the correct element types with associated properties and relationships). Also, as shown in Figure 14, Import Maps can be managed in groups, so regardless of the scope or scale or updates being imported from a spreadsheet, it can be done with one import.

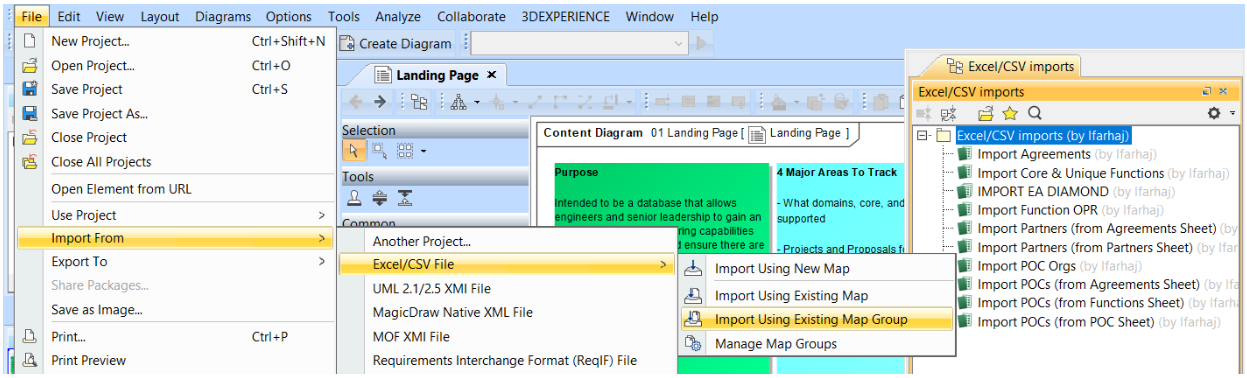

Figure 14. Import Map Selection.

This approach aligns with the Agency's goals of DET. Considering NASA's DE Need statement, the Strategy Map model and additional capabilities applied better manages complex, interconnected information, requires fewer man-hours, integrates various tools and processes, and supports seamless information flow. This is all part of the overall accomplishment of creating a data-centric alternative to past methods. Instead of multiple disjoint sources of information, the model acts as a FSoT that can produce various artifacts according to user needs. As a result, there is significantly more information captured—and thus, more potential use cases with various combinations of information—than previous documentation. Despite the increase in information, however, it is still notably easier to access and manage, regardless of a user's role. The modeler in MagicDraw can easily reference other work or let the project be used as a reference elsewhere with Project Usages. Model reviewers can choose between multiple options of reviewing the model and directly importing corrections back without even needing access to the model itself. This increases the maintainability and functionality of the model, and considering the low barrier of entry for end users, enables even more collaboration.

Summary

This paper highlighted NASA's journey in understanding one aspect of what Digital Engineering Transformation means for the Agency, the benefits of this transformation to human exploration definition and planning, and the benefits to the current Artemis Campaign engineering capability portfolio. Rather than using a document-centric approach to SE where data and information is managed in document silos and chronically out of date and inconsistent, NASA is transitioning to a data-centric practice of SE.

As a result, NASA M2M and supporting Programs and institutional organizations across the Agency are now able to manage, share, and leverage a FSoT set of data and information across large and complex human exploration missions made up of a SoS in ways which are lower risk and less cost and schedule prohibitive. In an organization as large as NASA with missions and Programs which span decades made up of systems that are part of the SoS that have separate funding and developing organizations, it is critically important the data-centric practice of SE and use of modern requirement management and modeling tools, structured data, and data threads that form a FSoT be implemented now as part of NASA Digital Transformation to ensure successful outcomes and that NASA remains a valued and preferred partner.

Doing so enables NASA to help mitigate the risk and lower expenses associated with space exploration, science, and discovery to the point where industry and international partners will be willing and able to profitably take on larger, more complex missions.

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Biography

Terry R. Hill. Serves as NASA's Digital Engineering Program Manager out of Office of Chief Engineer / HQ and is responsible for providing an executable strategic and implementation approach for delivering the strategic vision and implementation plan for digital engineering and MBSE methodology across NASA's Engineering domain.

Audrey Morris-Eckart serves from the NASA Johnson Space Center Systems Engineering Division where she manages teams of engineers and integrates technical representatives from the Engineering Directorate.

Alanna E. Carnevale. Serves as the MBSE lead for NASA's Exploration Systems Development Mission Directorate (ESDMD) Strategy & Architecture Office (SAO). She is responsible for architecture-level data development and refinement as well as the definition of new concepts and systems and their path to achieving a successful Mission Concept Review with MBSE.

Vinodini Sundaram is the Senior Lead Engineer at Booz Allen Hamilton and serves as the MBSE lead for the Moon to Mars SE&I team. As part of the Digital Engineering effort, she is responsible for reflecting and integrating the technical baseline across the Artemis architecture.

Leon Farhaj. Serves as a model-based systems engineer at Jacobs Solutions Inc. and is currently supporting NASA's lunar rover VIPER. Previously he was a system engineering intern for NASA's Johnson Space Center's Project Management and Systems Engineering Division.