AIAA SPACE Forum
31 Aug-2 Sep 2015, Pasadena, California
AIAA SPACE 2015 Conference and Exposition

AIAA 2015-4617

Inheriting Curiosity: Leveraging MBSE to Build Mars2020

Elyse Fosse[1] and Corey Harmon[2]
Mallory Lefland[3] and Robert Castillo[4]
and
Ann Devereaux[5]

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91101

The success of the Jet Propulsion Laboratory's (JPL) Martian mission Mars Science Laboratory (MSL) prompted NASA to challenge JPL to build a second rover, Mars2020. Mars2020 has chosen to infuse Model Based Systems Engineering (MBSE) in pursuit of aiding the design of the Flight System. This paper will derive the motivation for MBSE infusion and will explain the current state of the Mars2020 Flight System Model. Successes in MBSE adoption will be discussed, as will limitations to the methodology.

I. Introduction

On August 6, 2012 the Jet Propulsion Laboratory's (JPL) rover Mars Science Laboratory (MSL), also known as Curiosity, successfully landed on the Martian surface, beginning it's geological and environmental study of Mars in pursuit of finding evidence of a past environment well-suited for supporting microbial life. The landing was designed to be autonomous, the spacecraft self-steering through Mars' atmosphere, deploying a parachute, and finally enacting a sky crane that lowered the upright rover on a tether to land on its wheels. In less than a year from this harrowing landing, Curiosity had already met it's major science objective and continues on, analyzing Martian samples drilled from rocks or scooped from the ground via onboard test chambers inside the analytical instruments.[1]

The success of MSL prompted NASA to challenge JPL to build a second rover, for a fraction of the price of the first one. This new mission, currently named Mars2020, inherits a majority of MSL's Flight System (FS) design but has new science instruments designed to seek signs of past life on Mars. Furthermore, this mission will collect and store sets of soil and rock samples that could be returned to Earth in the future and the mission will also test new technology to benefit future robotic and human exploration of Mars.[2] Mars2020 must maximize its MSL heritage in order to meet the project's cost requirements, including not only buying heritage hardware early and reusing software but also capturing the subject matter expert knowledge that enabled mission success. In conjunction with the heritage paradigm, Mars2020 must also navigate the new risks associated with the new science instruments, technology demonstrations, and the introduction of the never before done sample caching system.

Early on in development, Mars2020 found use in capturing MSL lessons learned with regards to Systems Engineering. Most lessons revolved around the inadequacy of information capture. The technical baseline was captured using "boxology," slides and viewgraphs that lacked rigor or common terminologies and were constantly in danger of becoming out of date. The Systems Engineering design documentation, such as the System Block Diagrams and Electrical Interconnection List, struggled to stay up to date with the as-built configurations. Additionally, the MSL launch slip of two years resulted in significant artifact and personnel discontinuity that proved difficult to recover from pre-launch. Recognizing these difficulties and creating Mars2020 goals resulted in the desire for the Mars2020 Flight System Systems Engineering (FSSE) team to create an integrated technical baseline that could capture both MSL's as-flown design accurately, as well as the new designs of the science payload and sample caching system. The team wanted to provide an authoritative source of FS information that

---

[1] M2020 FSSE Engineer/FSMBSE CogE, Mission Systems & Operations, 4800 Oak Grove Drive/321-400,Member.
[2] M2020 Deputy FSSE Lead, Systems Engineering & Formulation, 4800 Oak Grove Drive/321-400, N/A.
[3] M2020 FSSE Engineer, Systems Engineering & Formulation, 4800 Oak Grove Drive/321-400, N/A.
[4] M2020 FSMBSE Facilitator, Systems Engineering & Formulation, 4800 Oak Grove Drive/301-390, N/A.
[5] M2020 FSSE Lead, Systems Engineering & Formulation, 4800 Oak Grove Drive/321-400, N/A.

could be easily accessible by the entire project, thus eliminating the danger of information silos and improving the visibility and traceability of technical baseline changes.

The Mars2020 FSSE team has chosen to leverage the advancements in MBSE to garner a better understanding of the complexities facing the mission. This paper will further elaborate MSL SE lessons learned and M2020 FSSE goals in order to explain the Flight System Model Based Systems Engineering (FSMBSE) approach.

The process of taking as-flown MSL information and populating the Flight System Design Model (FSDM) will be discussed and examples of the current set of model-generated products that are being used by the project will be presented. An explanation of incorporating new payload or sample caching information will follow. Barriers to MBSE adoption will be discussed and the paper will conclude with a discussion of evolving the state of practice to include better visualizations of the complex Mars2020 FSDM.

II. From MSL to Mars2020

The M2020 FSSE team members who worked on MSL embarked on a lessons-learned process that culminated with a list of SE challenges that M2020 would like to improve upon:

Technical baseline by "boxology": The technical baseline was captured using disparate visual representations, none of which were meant to explain the cohesive design. A rectangle in one presentation could be represented as line in another, with no explanation as to how the two related. Compounding the issue were the various tabular views of the technical baseline that lacked an integrated nomenclature. Interpretation of the visuals/tables was left to the consumer of the information, leading to an increased risk of late development discovery of design problems.

Information silos: A large team was required to manage the complexity of the spacecraft. Team members managed information locally and then periodically reported on their knowledge of the spacecraft to management and other team members. The existence of local design storage led to silos where the larger team was highly dependent on the availability of the information owner to communicate the knowledge. While there were shared repositories that team members contributed to, staleness of that information was always a concern and the typical method of operation was to contact the information owner via email to get the most up to date knowledge. The information silos also contributed to a lack of consistency when describing the design of the spacecraft. Certain subject areas would report knowledge at a greater detail than others, leaving it to the consumer of the information to reconcile the inconsistencies.

Personnel/Artifact discontinuity: MSL experienced a launch slip in 2008 and as a result the majority of personnel working on the mission transitioned to different projects. Their collective knowledge was lost and when MSL began to re-staff there existed a large discontinuity among understanding what work was completed and documented prior to the launch slip, the location of the documentation, and what work was left to go. Uncertainty in terms of the correctness of the disparate documentation coupled with the discontinuity contributed to an increased risk to the project.

Trades/concurrent engineering: As the spacecraft design progressed it was made apparent that the full scope of work was difficult to quantify. The difficulty was partly attributed to the fact that the spacecraft design maturity varied throughout the system, making it hard execute parallel trades and concurrent engineering.

SE product alignment and relevance: It was often the case that the work that the SEs were focusing on was not relevant to the SE products that needed to be delivered. The bifurcation between products requested for management or reviews and actual design work led to the SE team having to periodically stop or diminish their engineering work to focus on creating the necessary tables, diagrams, and charts by hand. This hindrance became most apparent during the months leading up to launch when the SE products, which were not integrated with each other, nor the as-built information, and stored in various repositories, struggled to keep up with the as-built spacecraft. During this time the project focus was on testing and launching the spacecraft, not documentation. As M2020 is inheriting the MSL design documents, the project is also inheriting the task of updating all SE products to represent the MSL as-flown/as-built configuration.

It is important to note that the Mars2020/MSL SE challenges are not unique to these flight projects. The broader Systems Engineering community has lamented the struggle of integrating interdisciplinary information and managing highly complex projects with the current SE processes and analytics.[3]

Based on these lessons learned the Mars2020 FSSE team aims to diminish the barriers associated with communicating the FS technical baseline. One aspect of communicating the technical baseline is accurate capture of the MSL as-flown design and the creation of FSSE products that are consistent with each other, both in terms of information content and layout. Another aspect involves improving the communication, understanding, and visibility of the FS design. The communication improvements are being pursued by providing an authoritative source of information that is accessible by the entire team (thereby reducing information silos and decreasing the impact of personnel discontinuity) as well as by defining a common language whereby the system can be described.

The Mars2020 FSSE team technical baseline communication objectives informed the creation and maintenance of FS design information in a Systems Modeling Language (SysML) model. The initial focus of the FSDM was on the changes to the MSL heritage design. The Mars2020 FS is comprised of a cruise stage, a descent stage, and the rover vehicle. The rover is the main component of the FS that is deviating from the MSL heritage design due to the accommodation of new science instruments and sample caching system. This resulted in the rover becoming the main focus of the initial FSMBSE effort.

III. Mars2020 Modeling Framework

A Mars2020 specific extension, or the Mars2020 Modeling Framework, of SysML was created in response to the desire to have a common language for describing the system. Most of MSL's design artifacts were captured in non-integrated tabular views, therefore it became important for the FSDM creation that the relations between the information contained in the views was understood. The Mars2020 Modeling Framework defines the expected model elements as well as the allowable relations among them. The framework extends a generic SysML embedding for Systems Engineering[4] as well as JPL-specific frameworks, where applicable, such that the nomenclature used is familiar and specific to Mars2020. The patterns within the framework are defined using a combination of stereotypes and the application of these stereotypes to reference model elements, also known as base elements. The Mars2020 Modeling Framework was constructed such that it could be extendable to meet the project's needs as Mars2020 progresses through its lifecycle. The current content of the framework focused on the patterns necessary to support the FSSE products that need to be delivered during the current early development phase of the mission. Extension of the framework will occur as the design matures and the SE products transform from trade studies and baseline design identification into an analysis of the design.

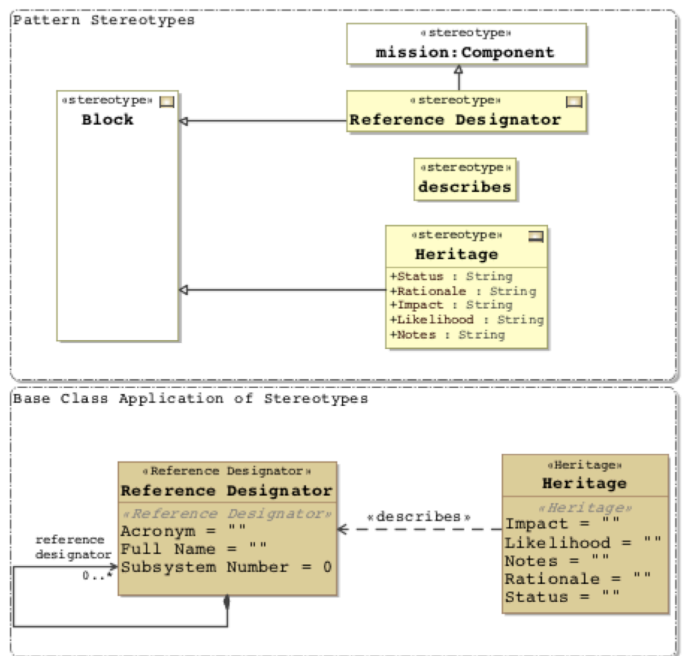


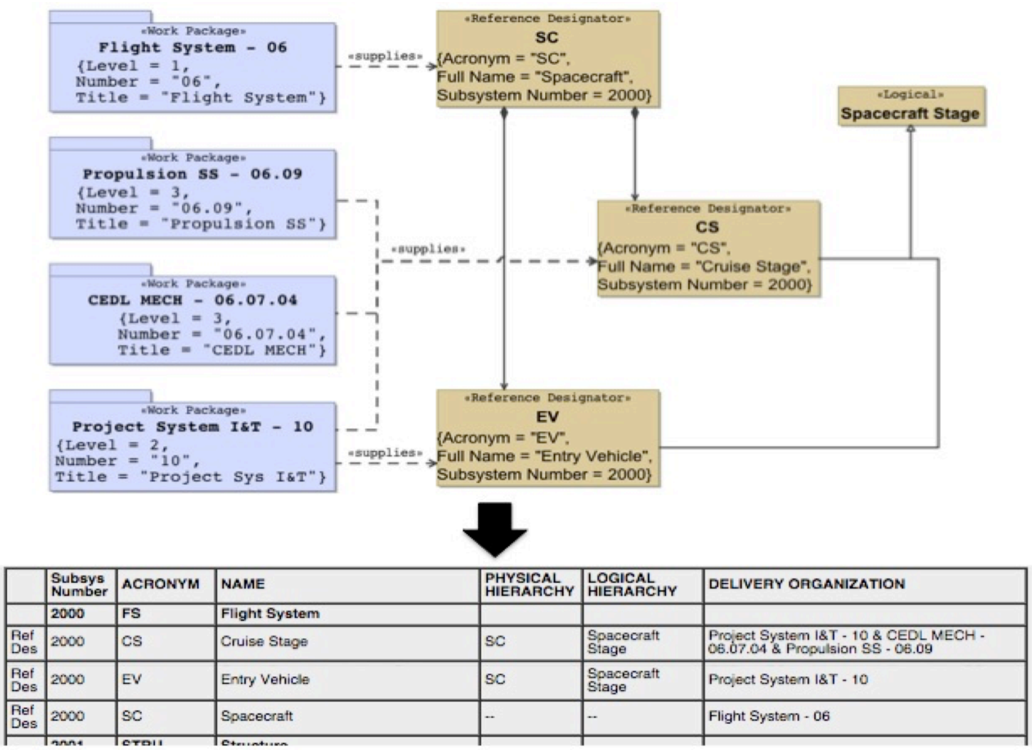
Figure 1. Mars2020 Modeling Framework. *The stereotypes in yellow are the M2020-specific stereotypes, extended from other domains (the stereotypes in white). The base class application illustrates the model element pattern utilization of the stereotypes.*

A Reference Designator is the main component Mars2020 is using to describe the physical flight system. It allows for the design to refer to physical components without fully specifying the physical object (e.g., part number, or other specifications that are only known post-procurement). Utilizing the concept of a Reference Designator as the main component provides the project with the ability to describe many aspects of the design using a common thread. Interfaces, mass, heritage, and even change control all relate to Reference Designators. In that vein, the framework defines a Reference Designator to be the primary object of the pattern and all other objects have patterns defined to relate them to one or more Reference Designators. The framework allows for Reference Designators to be related to each other in two ways: with respect to their physical composition on the spacecraft and with respect to their electrical connections. Reference Designators can also be characterized by their respective mass and MSL heritage designation. A pattern for identifying and relating organizations that are responsible for delivering and testing each Reference Designator is also provided.

The framework also includes a set of python scripts that are used to validate the implementation of the patterns in the FSDM. The benefits of validating against the patterns defined in the framework are two-fold: SEs have confidence that they are implementing the pattern correctly and SEs can ask questions about completeness and work left to go in a quantifiable manner. All of which allows for the FSSE team to assign some level of confidence about the technical baseline design capture. For example, a validation rule is written that checks the given SysML model for any Reference Designators that do not have a relation to another Reference Designator. In terms of the technical design, this implies that it is unknown where the physical component resides within the physical hardware architecture and that there might be missing electrical connections. A FSSE can run the validation rule, examine the validation error log, and make the engineering assessment as to whether the errors are a misunderstanding or flaw of the design or known work to go.

IV. Model-Generated Systems Engineering Products

While maintaining the Flight System design within a SysML model allows the FSSE team to view and design against integrated information, it is through the generation of model-based FSSE products that the issues of information silos, inconsistent information, and lack of product consistency are greatly reduced, if not eliminated entirely. The broader MBSE community has made significant advancements towards extracting document artifacts



	Subsys Number	ACRONYM	NAME	PHYSICAL HIERARCHY	LOGICAL HIERARCHY	DELIVERY ORGANIZATION
	2000	FS	Flight System			
Ref Des	2000	CS	Cruise Stage	SC	Spacecraft Stage	Project System I&T - 10 & CEDL MECH - 06.07.04 & Propulsion SS - 06.09
Ref Des	2000	EV	Entry Vehicle	SC	Spacecraft Stage	Project System I&T - 10
Ref Des	2000	SC	Spacecraft	--	--	Flight System - 06

Figure 2. Document Generation. *Python scripts traverse the FSDM and project the M2020 Modeling Framework patterns into tabular form. The broader project audience refers to the model generated documents for design information. In this case, the different types of model elements (Work Package, Reference Designator, and Logical and their relations to one another are projected into a table, where each row identifies a Reference Designator and its respective relations to the other model elements.*

from a SysML Model,[5] all of which Mars2020 is leveraging. Through SysML viewpoints and python scripts the FSSE team is able to project the FSDM into the tabular views that are expected and familiar to the broader consumers of the FS design information. The model information is validated each time the viewpoint is executed, ensuring that the provided document is correct and complete with respect to the Mars2020 Modeling Framework. Examples of such products being generated currently are the Reference Designator Table, Electrical Function List, and the Mass Equipment List. The same information that is used to generate those lists is also used to derive summary reports, such as the Interface Resource Metrics List (identifies spare and connected electrical interfaces) and the Mass Trending Report (summarizes the current mass of the spacecraft and displays plots for spacecraft mass over time). These model-generated documents are then made accessible via a web interface. The web interface provides the capability to generate documents on demand or on schedule, view the document in pdf or html formats, and allows for the tagging of specific document generations for archival. [6] The document generations are also used as way to infer the state of the model, documents failing to generate or documents with validation error logs imply that the FSDM needs to be examined for errors. The ability to generate these documents on an as-needed and scheduled basis allows for issues within the FSDM to be discovered in a timely manner.

A significant amount of work has been done by the FSSE team to understand how to leverage SysML viewpoints in order to generate model-based diagrammatic views of the FSDM. Current MBSE practice is to create SysML diagrams, such as an Internal Block Diagram, within the software tool that is being used to apply SysML. The downside of this methodology is that diagrams are still maintained by hand. As the technical information is changed within the model, the diagrammatic representation decays and the time consuming process of updating the diagram is left to the FSSE. There currently does not exist a capability that would allow the FSSE to guarantee consistency or completeness of a diagrammatic product. Another detriment to the current MBSE practice that the FSSE team has found is that SysML diagrams do not effectively communicate the FS design to a broader audience. The majority of project members do not want to see a SysML port when looking at a view of electrical connectivity, for example. While ports are semantically correct and beneficial for modeling the electrical functions, their presence in a diagram is not a necessity for reviewing the FS design with a larger audience. It is not possible with SysML and SysML tooling alone to provide the correct level of abstraction of the FS design for audience consumption and thusly the team still reverts to non-semantically driven tools (e.g., PowerPoint) to produce content needed for reviews or presentations.

The FSSE team has begun using commercially available graphical representation software to enable the automatic generation and layout of diagrams. Through the use of this tool, Tom Sawyer,[7] the team is able to enforce rules on the presentation of elements (e.g., all 1553 data connections should be represented as blue, dotted lines) as well as the layout of elements (e.g., all rover avionics boxes should be inside the rover structure). An added benefit is these diagrams can either be deployed statically as pictures for document inclusion or dynamically as a web-based interactive application. The addition of model generated diagrams into the Mars2020 MBSE toolbox has reduced the amount of time FSSEs have to spend on maintaining such typical "Power Point" views of the system and have provided a venue for exposing the technical design to a broader audience agnostic to any knowledge of SysML or MBSE.

After updating the technical design information within the model, it is simply with a push of a button that the model-generated products can be updated with the new engineering content. Providing timestamps informs the broader audience about the staleness of the design information they are viewing and enables them to use their engineering judgment as to how to proceed with the information. Processes have been implemented to ensure the cadence with which the model-based documents are generated reflect the cadence to which the technical information is changing.

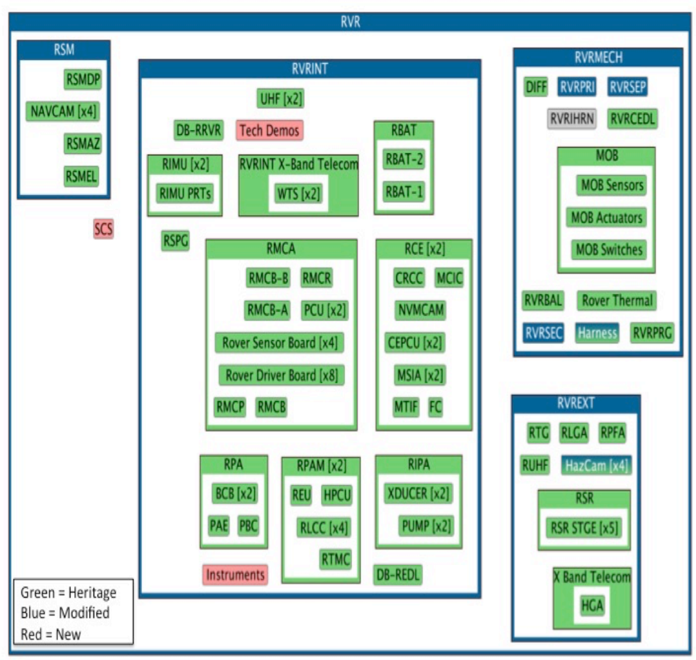


Figure 3. FSDM Visualization Example. *An example view of the FSDM utilizing rule based color-coding of MSL heritage and automatic layout of Reference Designators in Tom Sawyer. The visual allows for easy assessment of heritage levels, even with new Reference Designators being added to design.*

V. MBSE Adoption and Infusion of New Information

The FSDM has begun to evolve beyond capturing as-flown MSL design and is being utilized to capture the design aspects of the new flight system hardware, namely the new science instruments and sample caching system. The framework has been extended to allow for reference designators and electrical functions to be characterized as notional, thereby allowing the FSSE to maintain the less mature, more likely to change, information within the same modeling environment as the heritage design while also enabling the capability to filter out these design aspects when generating FSSE products for broader audience consumption. The fact that the effort has gone into capturing accurate design information of the heritage Reference Designators, interfaces, and mass allows the FSSE team to spend the majority of their time focused on the new elements of the design. Additionally, consumers of the FS design are starting to extend the FSDM into their particular subject matter expertise. There is an End-to-End Information System (EEIS) prototyping effort underway that is looking to connect the FSDM's data interface information to Mars2020's relay asset design and extending that further to connect to a Ground Data System (GDS) model. The culminating EEIS model will empower a more rigorous assessment of the operational differences between MSL and Mars2020 due to the potential obsolescence of one communication orbiter and the addition of two new communication orbiters.

When the FSDM effort began two years ago, a large portion of the FSSE team was unfamiliar with SysML and the accompanying modeling software and correspondingly the six MBSE practitioners infused into the team were not familiar with FS design practices. To begin, the staff of six MBSE practitioners populated the FSDM with MSL as-flown design information. Within six months the framework was defined, a large quantity of the FSDM was created, and preliminary documents were generating from the FSDM. At that time all MBSE practitioners besides one moved to other projects, resulting in the remaining FSSE team members maintaining and contributing to the FSDM. A barrier to entry into MBSE for the FSSE team is that no one needed to be in the FSDM everyday and as a result retaining training information became imperative. The team has attempted to dampen this barrier by maintaining a FSSE MBSE wiki portal that contains links to pertinent software, websites, documentation and video tutorials of pattern implementation processes, and an overall narrative that explains the motivation and expected results out of the effort. Currently, the FSSE team members who are the owners of the information contained within the FSDM interact with the model to maintain their respective aspects of the FS design. The MBSE practitioner, with the expertise of another MBSE facilitator focus their attention on extending the information contained in the FSDM and supporting less formal design activities as requested by the team. Moreover, the MBSE practitioner has become responsible for FS design-specific work. The training was truly a bi-directional effort where the FS domain experts learned MBSE and vice versa.

There is still work to go in infusing MBSE into the daily workflow of a Systems Engineer. While the FSDM is the authoritative source to design against, FSSE team members are still looking to other tools to aid in their working design. The collaborative nature of the FSDM is one motivation for the desire to have access to the model information in a more sandbox manner. In the current toolset, one team member may lock the information for editing which restricts the ability for another to maintain their information. The static reporting of model information via documents is another motivation for a sandbox-like capability. The Mass Equipment List is reported via the model; however, the information owner must revert to another application, which duplicates the information in order to perform trades during meetings and if those trades are accepted they then need to update the model manually. The FSSE team is currently evaluating potential solutions towards integration with online model editing tools.

The FSDM has enabled the FSSEs to focus more on the difficult and complex engineering aspects of their work with a greater confidence that the information they are using is complete and recent. The FSDM and framework forced the disparate MSL as-flown engineering products to be harmonized into a cohesive flight system model. The benefit of which can be seen by the fact that the FSSE team is identifying inconsistencies, and thereby capturing and fixing design misunderstandings/errors early in the mission lifecycle. The inconsistencies would have been found regardless of an MBSE implementation but the cost to fix or risk to the mission could have been greater since they most likely would not have been found until fabrication or integration.

The capability to generate documents and visualizations from the FSDM has also enabled the FSSE team to interrogate the FS design through asking questions that normally would be time-intensive to answer and/or involve tracking down various owners of information. An example of one such question involves quantifying the risk of change to the rover electrical functions. Asking this question without the FSDM would have involved a lot of engineering judgment and comparisons between non-integrated tabular designs of the system. Leveraging the FSDM the team was able to derive the heritage classification for the electrical functions based on the heritage classification of the reference designators connected. There is still engineering judgment to be applied, but now engineers can quickly focus on the electrical functions that were not connecting reference designators classified as heritage. The owners of harnessing as well as the owners of the electrical circuit data sheets are using this electrical function heritage classification to inform their work schedule. If an electrical function is designated as heritage then the respective teams can embark on that design work with little risk that they will have to redo, whereas they may choose to wait on designing for an electrical function designated as new since that information has a greater risk of changing during the mission's early development phase.

VI. Conclusion

The Mars2020 Flight System adoption of MBSE methodologies to enable conquering of common SE challenges experienced on MSL is an ongoing effort. The implemented methodologies are summarized presently and related to the aforementioned SE challenges.

Mars2020 Modeling Framework: provides a common nomenclature that can be used to describe the Flight System by the entire project thereby providing precise, unambiguous communication of the design. Patterns provide a mechanism to easily extend and add to the Flight System design information and a mechanism for extracting document artifacts from the model. Validation rules provide a mechanism for identifying inconsistencies or discontinuities across the design information.

Model Generated Systems Engineering Products: eliminate artifact discontinuity by extracting the artifacts directly from the design information. Making the documents accessible via a web interface reduces information silos by providing a common location to access the Flight System design information.

Rule-Based Diagram Creation: eliminates the need for "boxology." Review or presentation artifacts can be projected directly from the FSDM and the concern of presentation layout and appearance can be dealt with separate from the actual FSDM SysML implementation. Making the FSDM visualization accessible to the greater team reduces information silos.

As the state of MBSE evolves, the Mars2020 Flight System will be looking to strategically infuse advancements in pursuit of a greater understanding of the flight system design.

Acknowledgments

U.S. Government sponsorship acknowledged. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1] "Mars Science Laboratory/Curiosity," National Aeronautics and Space Information Fact Sheet [online], http://www.jpl.nasa.gov/news/fact_sheets/mars-science-laboratory.pdf [retrieved 1 February, 2015].

[2] "Mission Concept: Mars2020." National Aeronautics and Space Information Fact Sheet [online], http://www.jpl.nasa.gov/news/fact_sheets/mars2020factsheet.pdf [retrieved 1 February, 2015].

[3] Hartmann, R., Belhoff, B., Oster, C., Friedenthal, S., Paredis, C., Kemp, D., Stoewer, H., Nichols, D., Wade, J., "A World In Motion, Systems Engineering Vision 2025," INCOSE, San Diego, CA, 2014.

[4] Jenkins, S. J., and Rouquette, N. F., "Semantically-Rigorous Systems Engineering Modeling Using SysML and OWL," NASA TR-20150005663, 2015.

[5] Jackson, M., Delp, C., Bindschadler D. Sarrel, M., Wollaeger, R., Lam, D., "Dynamic Gate Product and Artifact Generation from System Models," *IEEE Aerospace Conference,* IEEE, New Jersey, 2011, pp. 1-10.

[6] Delp, C., Lam, D., Fosse, E., Lee, C., "Model Based Document and Report Generation for Systems Engineering," *IEEE Aerospace Conference,* IEEE, New Jersey, 2013, pp. 1-11.

[7] Tom Sawyer Perspectives, Ver. 7.0, Tom Sawyer Software, Berkely, CA, 2015.