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Orion SysML Model, Digital Twin, and Lessons Learned for Artemis I

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Initial Problem Statement

- To ensure the safe and effective operation of complex space systems, engineering and operations personnel require insight into system design, configuration, and behavior.
- We need to understand what can/will/has gone wrong.
- Resource limitations have prevented the development of the conventional products that have historically provided this insight.
- Remaining products, which are meant for manufacture and verification, do not provide practical access to the required insight.

The current paradigm involves excessive work to just build and maintain the information, and it also takes a long time for users to access and digest the information.

- Agency leadership sees the promise of digital twin technology applied to complex aerospace systems.
- Digital modeling and integration of design can reduce the time answer questions by days and required human resources by an order of magnitude over historical approach.
- Few examples within NASA of wide-scale digital twin applications means value is difficult to demonstrate, lack of building-blocks to jumpstart development, and ‘technology readiness’ is too low for immediate utilization.
- Value must be demonstrated with example of the methods, tools, and language needed to implement an effective digital twin of a complex aerospace system.

Orion Spacecraft

Artemis I Flight Day 13: Orion, Earth, and Moon

Image Credit: NASA - images-assets.nasa.gov/image/art001e000678/art001e000678~orig.jpg

[Orion Spacecraft Overview - Artemis I](https://www.nasa.gov/sites/default/files/617409main_orion_overview_fs_33012.pdf)

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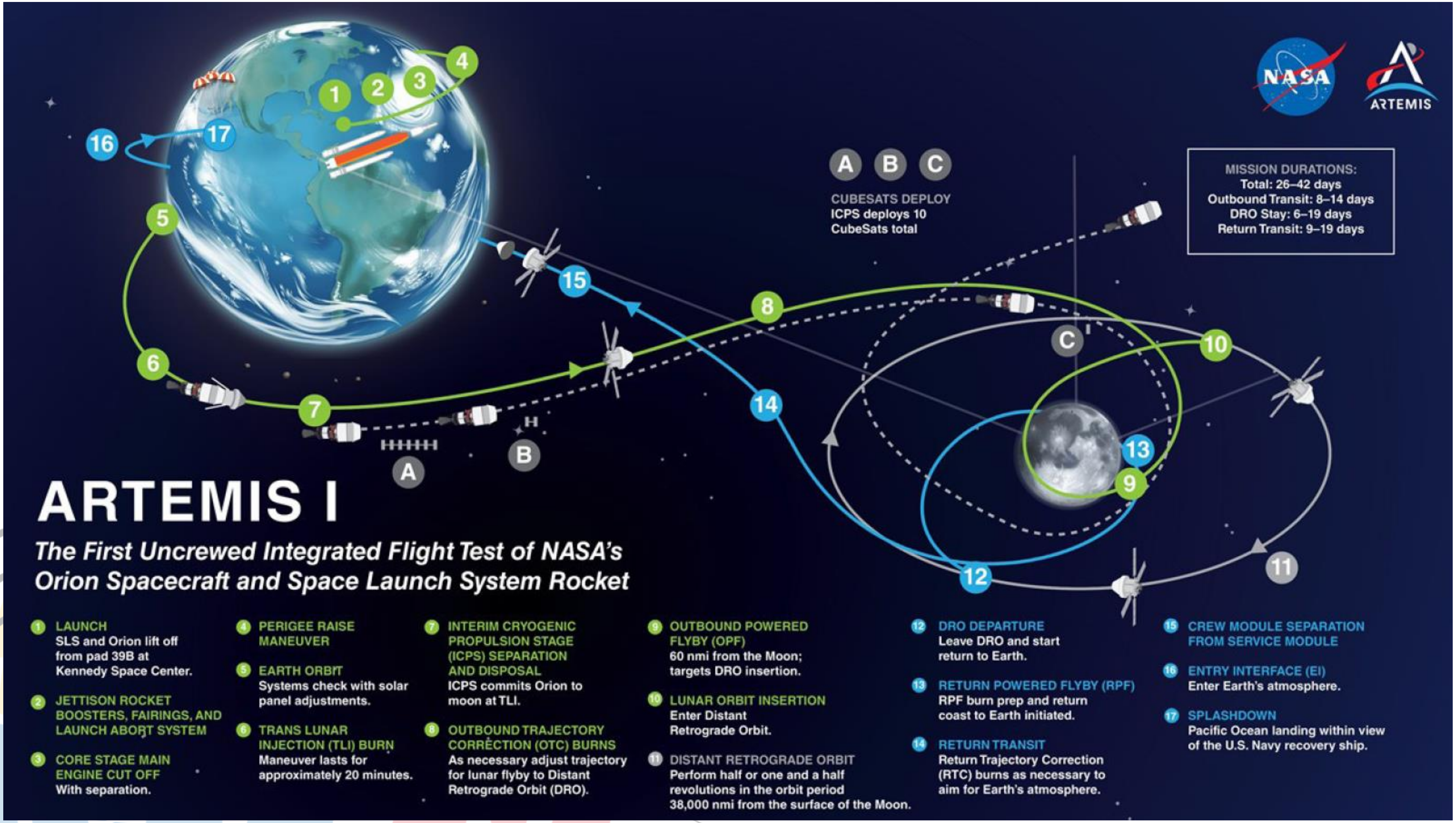


NASA
ARTEMIS
A B C
CUBESATS DEPLOY
ICPS deploys 10
CubeSats total
MISSION DURATIONS:
Total: 26–42 days
Outbound Transit: 8–14 days
DRO Stay: 6–19 days
Return Transit: 9–19 days
ARTEMIS I
The First Uncrewed Integrated Flight Test of NASA's Orion Spacecraft and Space Launch System Rocket
1 LAUNCH
SLS and Orion lift off from pad 39B at Kennedy Space Center.
2 JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM
3 CORE STAGE MAIN ENGINE CUT OFF
With separation.
4 PERIGEE RAISE MANEUVER
5 EARTH ORBIT
Systems check with solar panel adjustments.
6 TRANS LUNAR INJECTION (TLI) BURN
Maneuver lasts for approximately 20 minutes.
7 INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION AND DISPOSAL
ICPS commits Orion to moon at TLI.
8 OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS
As necessary adjust trajectory for lunar flyby to Distant Retrograde Orbit (DRO).
9 OUTBOUND POWERED FLYBY (OPF)
60 nmi from the Moon; targets DRO insertion.
10 LUNAR ORBIT INSERTION
Enter Distant Retrograde Orbit.
11 DISTANT RETROGRADE ORBIT
Perform half or one and a half revolutions in the orbit period 38,000 nmi from the surface of the Moon.
12 DRO DEPARTURE
Leave DRO and start return to Earth.
13 RETURN POWERED FLYBY (RPF)
RPF burn prep and return coast to Earth initiated.
14 RETURN TRANSIT
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere.
15 CREW MODULE SEPARATION FROM SERVICE MODULE
16 ENTRY INTERFACE (EI)
Enter Earth's atmosphere.
17 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ship.

The Digital Twin

A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.*

Functionality

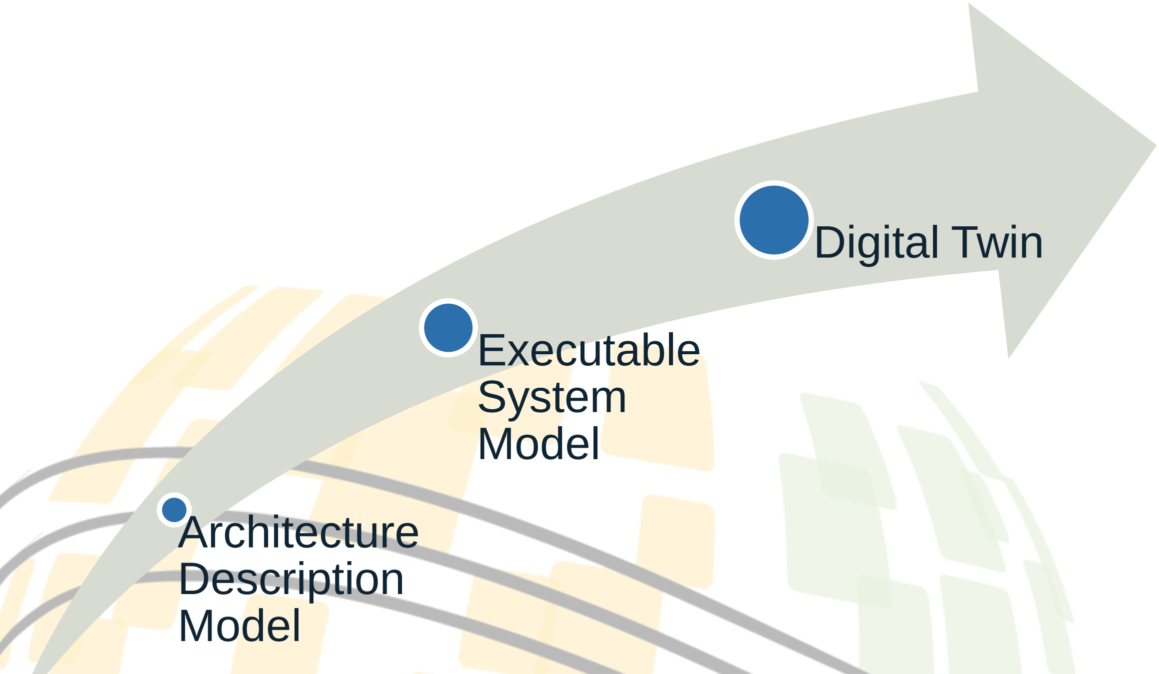
- Models structure, interfaces, and behavior of physical systems and processes
- Captures status and characteristics of the system via digital threads
- Co-locates related information regarding a physical system or process
- Performs real-world-calibrated simulations
- Captures historical performance trends and projects future performance
- Optionally, can be used to configure or command the physical system

Effects

- Provides insights that are otherwise difficult or impossible to obtain
- Accelerates decision velocity by orders of magnitude
- Improves quality of decisions
- Enables rapid deployment of new configurations

*Source: www.digitaltwinconsortium.org

From System Model To Digital Twin



Emphasis is on utilizing model-based systems engineering (MBSE) products as the basis of digital twins, encouraging:

- Development efficiency
- Authoritative source of truth
- Project integration
- Multi-domain analysis
- Interoperability

Orion Digital Twin Ecosystem

Twofold project goals:

Digital Transformation Office

- Define processes, methods, and capabilities of digital twin application on a large program

Orion Program

- Address program gaps/needs through digital twin platform
- Enhance human interface with data to enable increased data driven decision velocity and accuracy.

Approach

- Initially developed as a pilot project with the potential for mission-support certification
- Utilized system modeling tool MagicDraw® to create a foundation for a digital twin of Orion systems that is able to provide needed insight to the operations and engineering teams. This included:
  - Detail- and context-rich schematics
  - Web-accessibility in a COTS tool
  - System-level simulations
  - As-designed/As-tested/As-operated unit-specific data
- Development began with the Orion Electrical Power System (EPS).

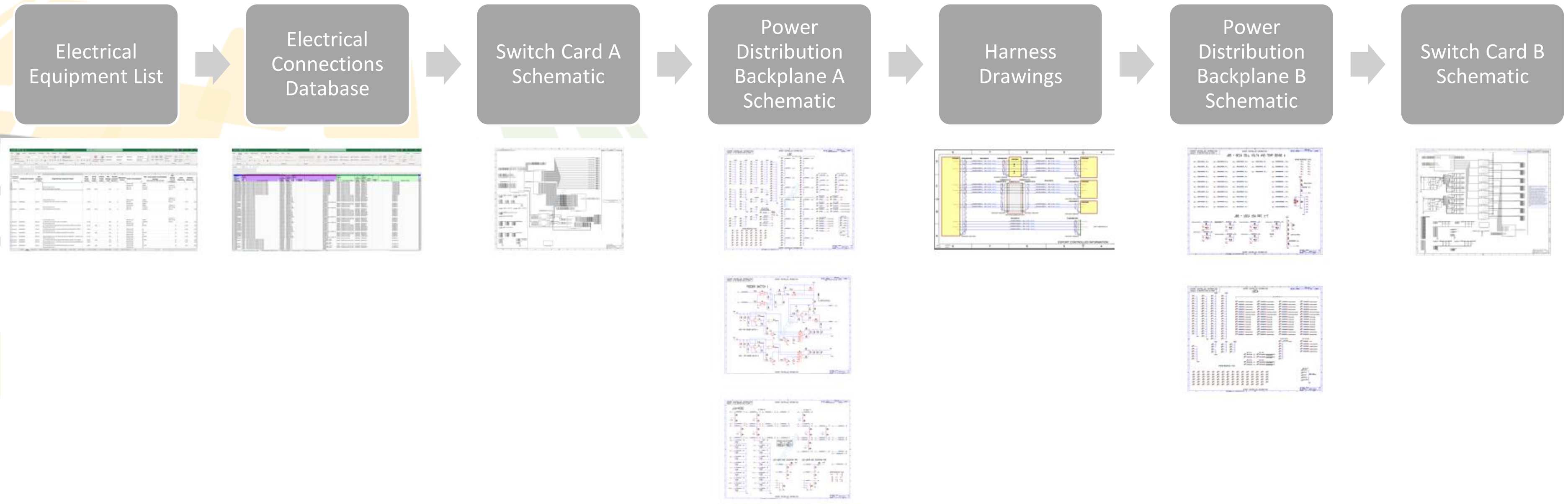
Goal of validated Orion EPS Digital Twin to be available during Artemis-1.

- Development could continue with additional Orion systems, such as Command & Data Handling, Communications & Tracking, and Life Support.
- Development could also proceed with the support of additional digital twin integration and simulation use cases.

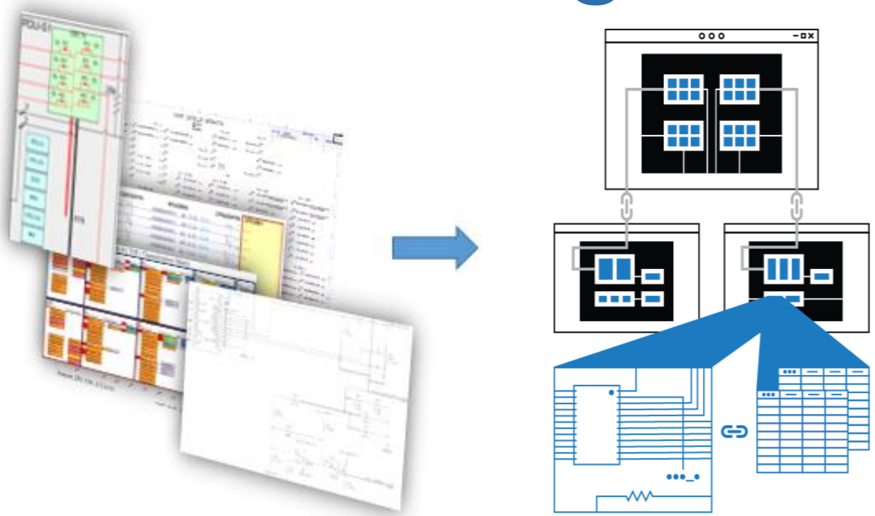
Status-quo of Document-Based Information Retrieval

- Use Case:
  - Troubleshooting electrical abnormalities from ‘Switch Card A’ on PDU-A to ‘Switch Card B’ on PDU-B
  - What does it take to find possible failure points from a load to a source?

Status-quo of document-based information retrieval



Benefits of Integrated Schematics



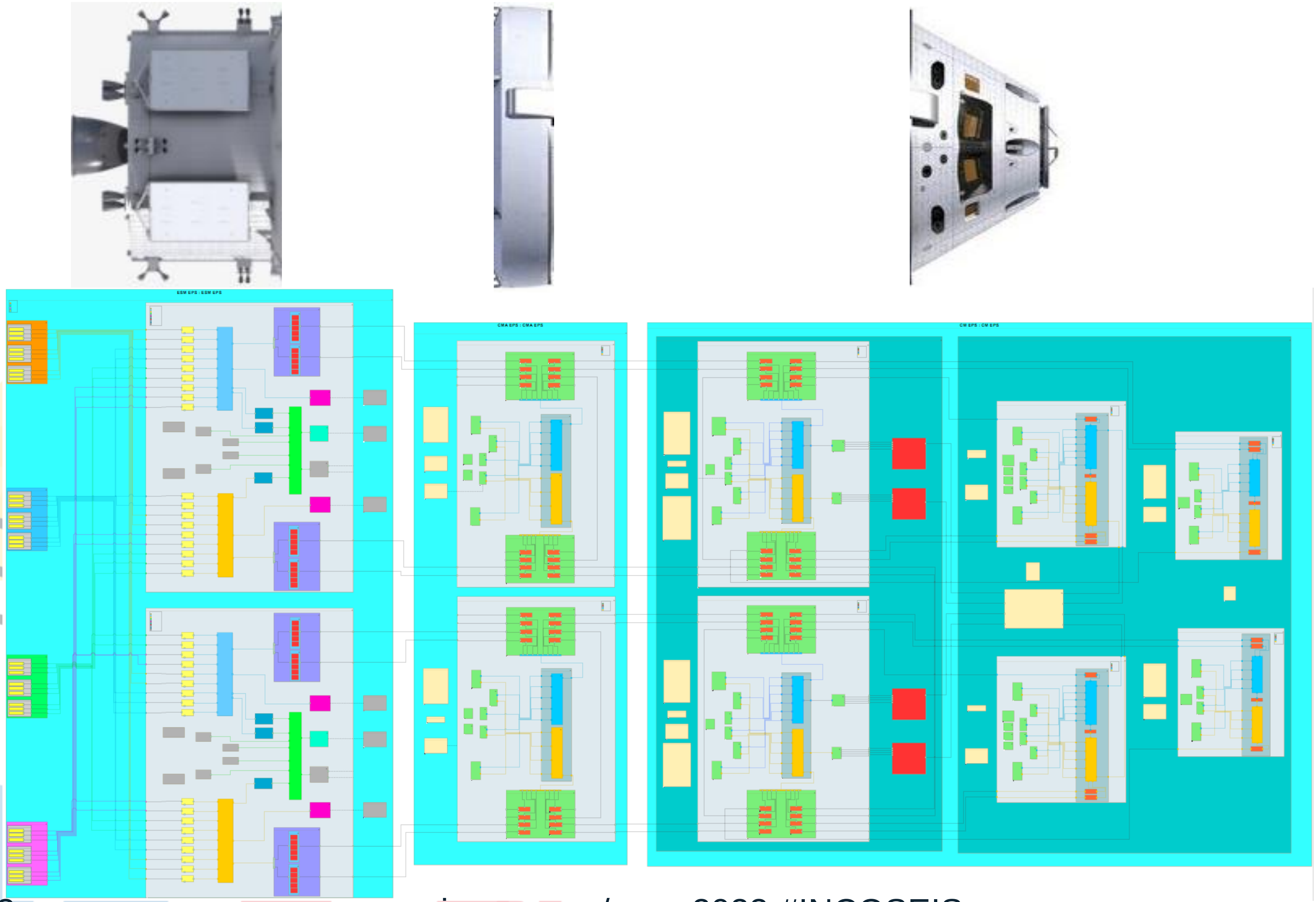
For the Engineer

- **Unified Channelization Data and Diagrams**
  - Diagram information stored in a parsable language (SysML)
  - Reduce errors caused by disjoint nature of document-based architecture
- **Automation**
  - Content generation
  - Report generation
  - Validation to authoritative sources

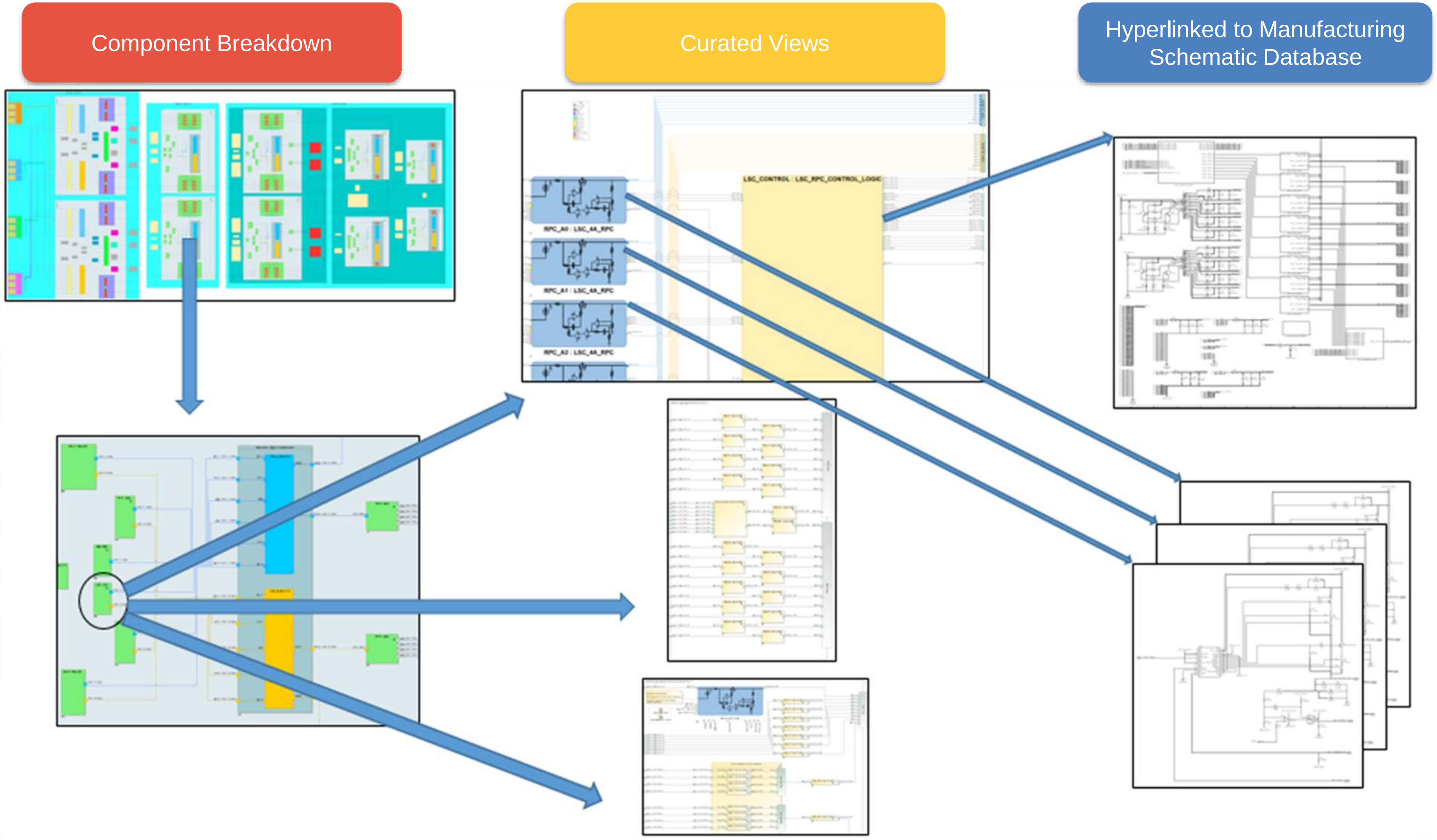
For the User

- **Intuitive Information Retrieval**
  - Tip-to-tail tracing of electron flow
  - Navigate through higher level architecture to lower-level schematics and component specifications
- **Ease of Access**
  - Access through internet browser
    - Available to all with NASA Single Sign-On Login
  - Provides platform for model-based reviews
    - Add/reply comments on diagrams
    - Comments sync with MagicDraw application

Orion EPS Architecture

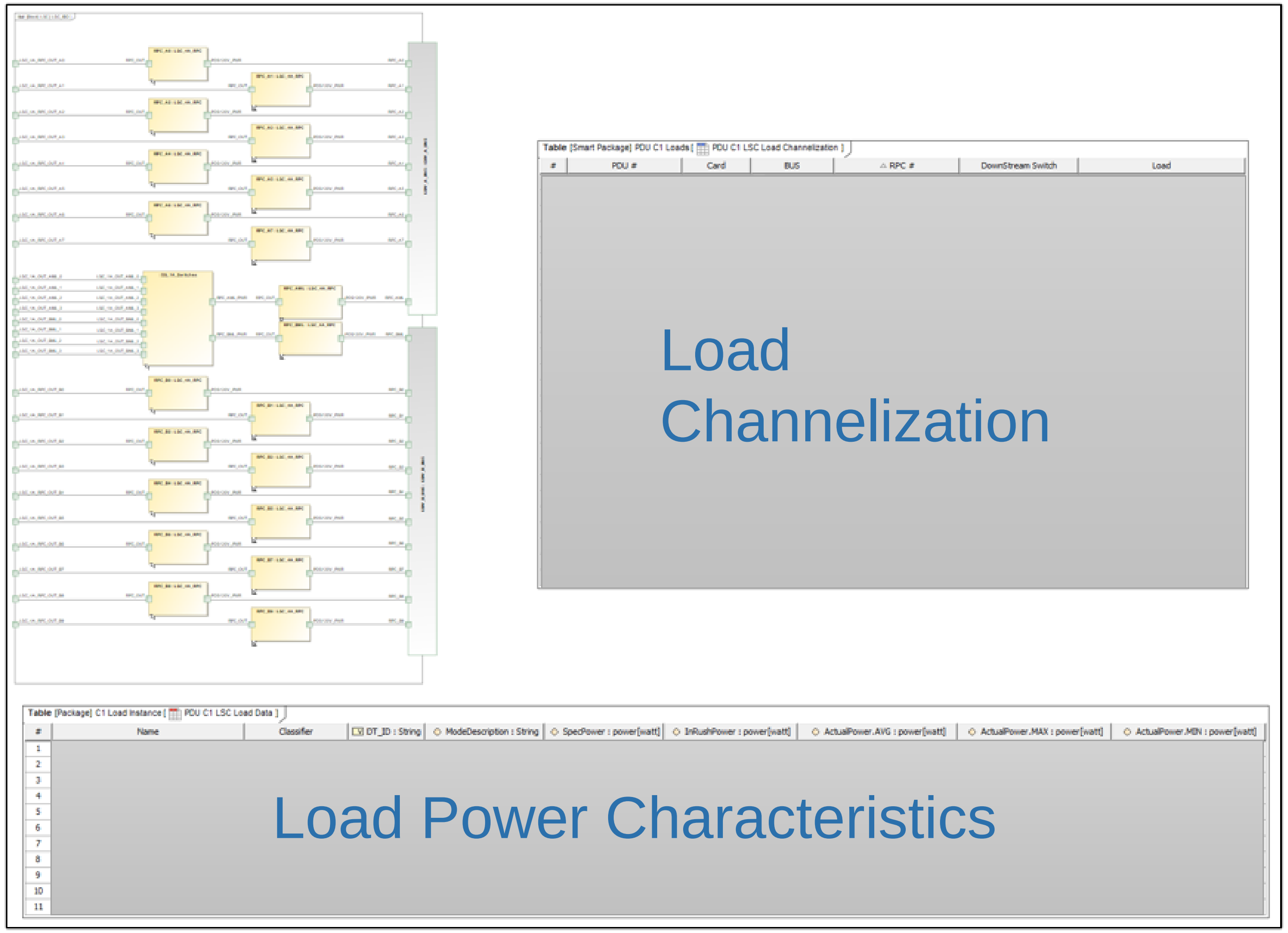


Integrated Schematics

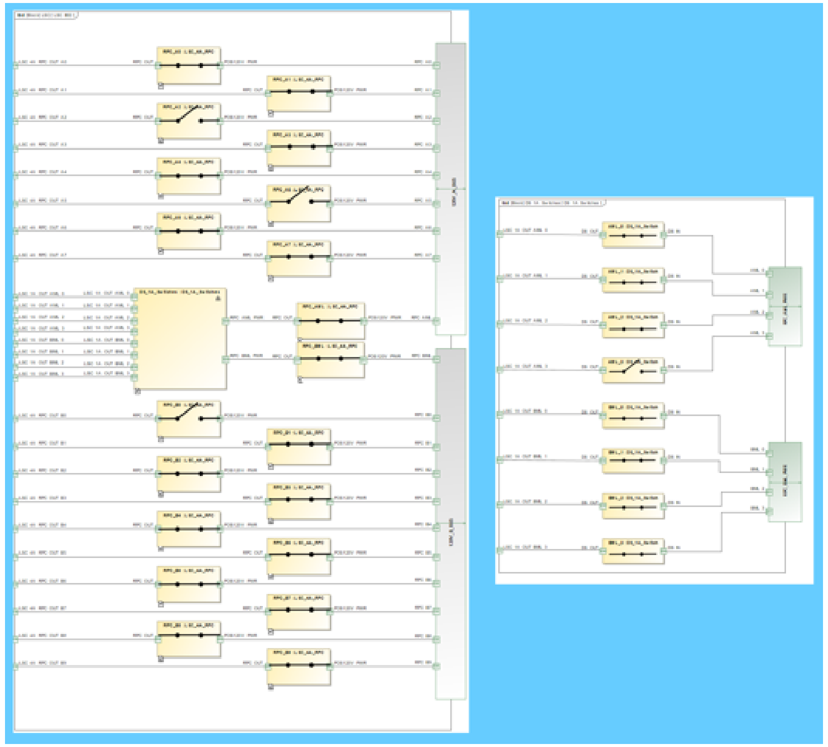


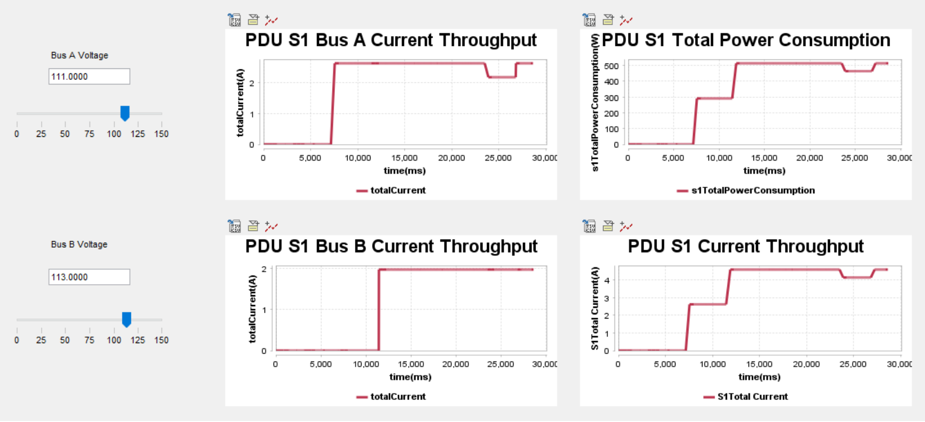
Curated Views Example- Channelization and Operational Data

- Single location for:
  - Diagrams
  - Reports/Queries
  - Component Data
    - As Designed
    - As Tested
    - As Operated

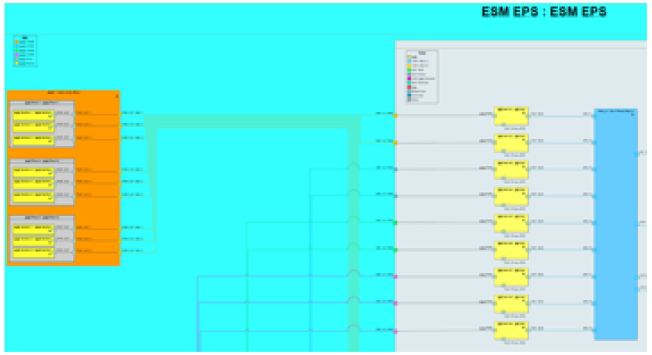


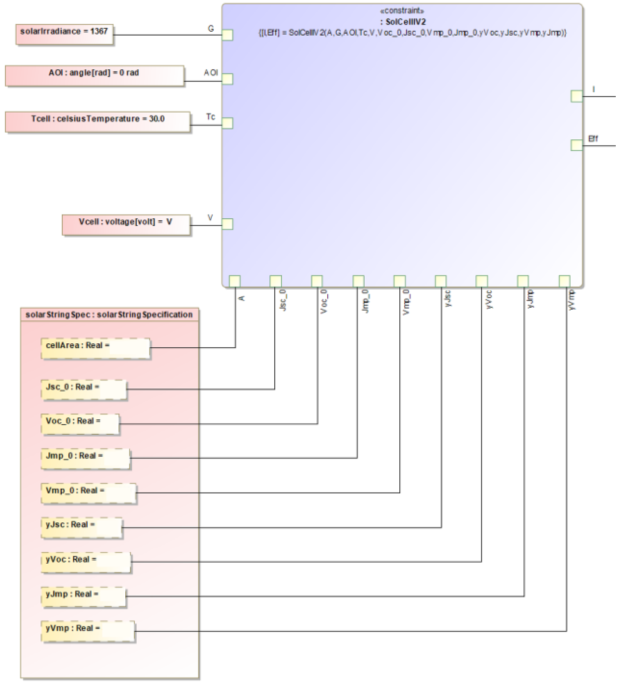
Integrated Simulation – Power Bus

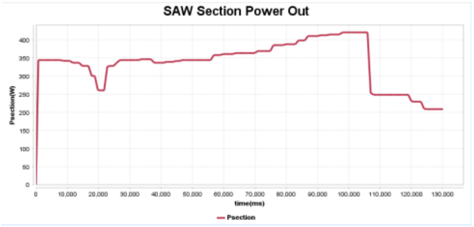


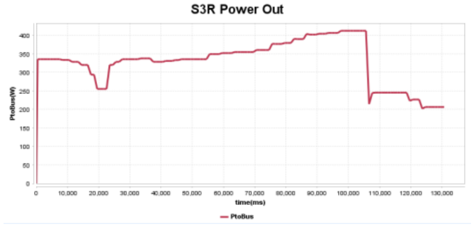


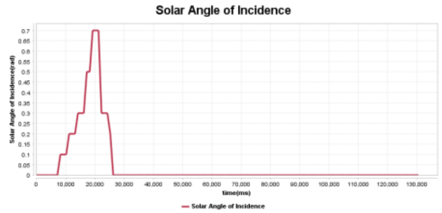
Integrated Simulation – Solar Arrays

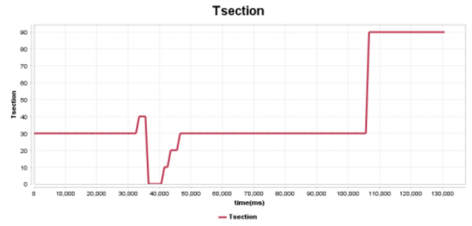


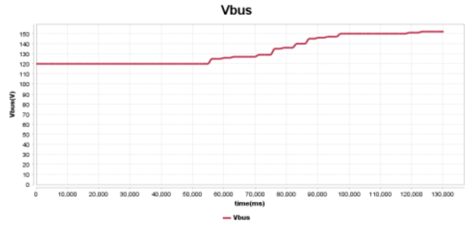












Artemis I Mission Validation

A series of evaluations was performed with the Orion Electrical Power System (EPS) System Management (SM) team

- Presented a hypothetical anomaly situation
- Utilized the Cameo Collaborator web application
  - Graphical comment feature in Collaborator was used to flag the anomaly, which was then accessed by the evaluator on the comments panel.
  - This demonstrated an efficient means of communication between flight controllers and system managers, as this built-in feature directly connects the user to flagged model elements for quick resolution.
- Evaluators used the dynamic navigation capabilities of the tool to explore the system for possible proximate causes for the anomaly as well as quickly accessing detailed design artifacts that were linked to the model.
- Each session ended with a short set of interview questions.

The evaluators found the tool powerful but approachable and especially liked the ability to dynamically navigate the system.

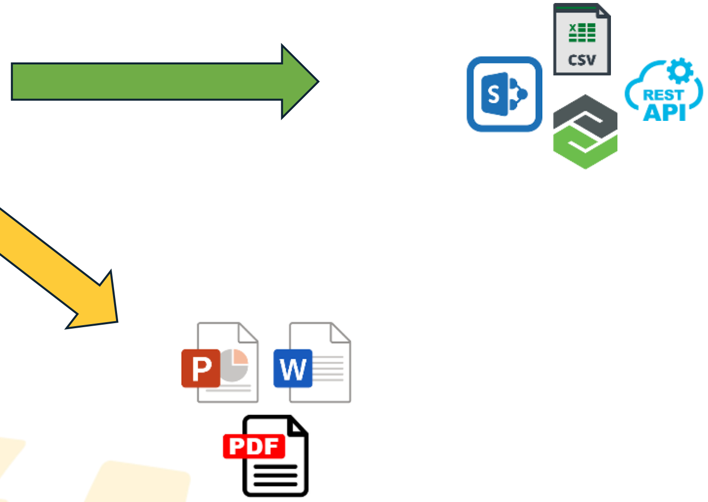
Orion Digital Twin Metrics

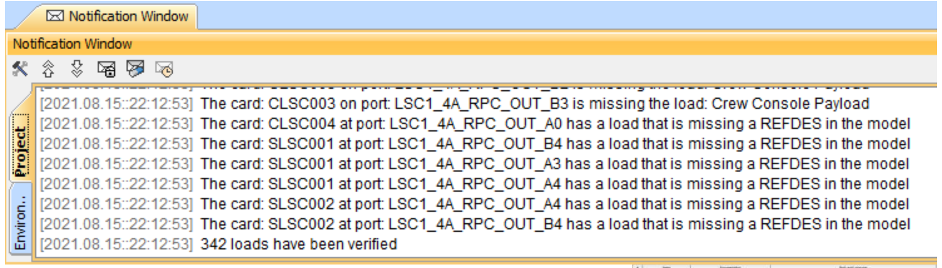
- Over 9,000 components represented
  - ~600 elements of definition reused
  - Over 130 hyperlinks to schematics database integrated into SysML Model
- Over 4,500 interfaces defined between components
- Over 500 loads integrated into EPS architecture
  - Channelization to specific switch within each power distribution unit
  - Individual load parameters
    - "Spec Power"
    - "Actual Power"
    - Etc.
- Automated syncing and validation of data and architecture to authoritative sources
- Simulation utilizing built architecture and imported component specifications

Lessons Learned Summary

- Synchronization with Design Artifacts
- Artifact Navigation
- Human Error Reduction
- Parametric Equation Solving
  - Deconflicting human-readable diagrams and MagicDraw equation solving
  - Functional Mock-up Unit (FMU) Integration
  - MATLAB Integration
- In-Model Scripting with Opaque Behaviors

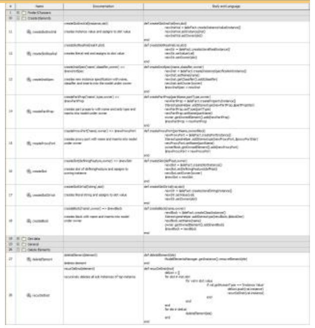
Lessons Learned: Synchronization with Design Artifacts

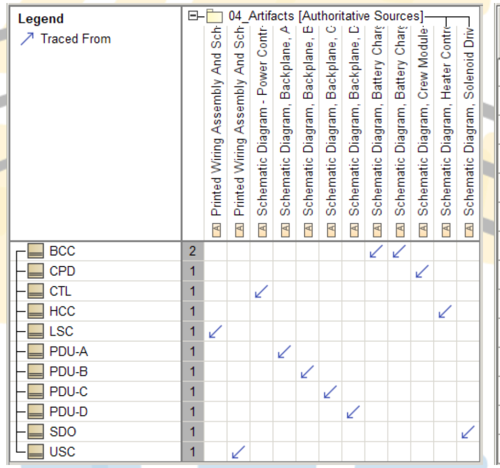




MagicDraw API Automation

- Component channelization validation
- Component parameter value sync
- Tailorable to input format





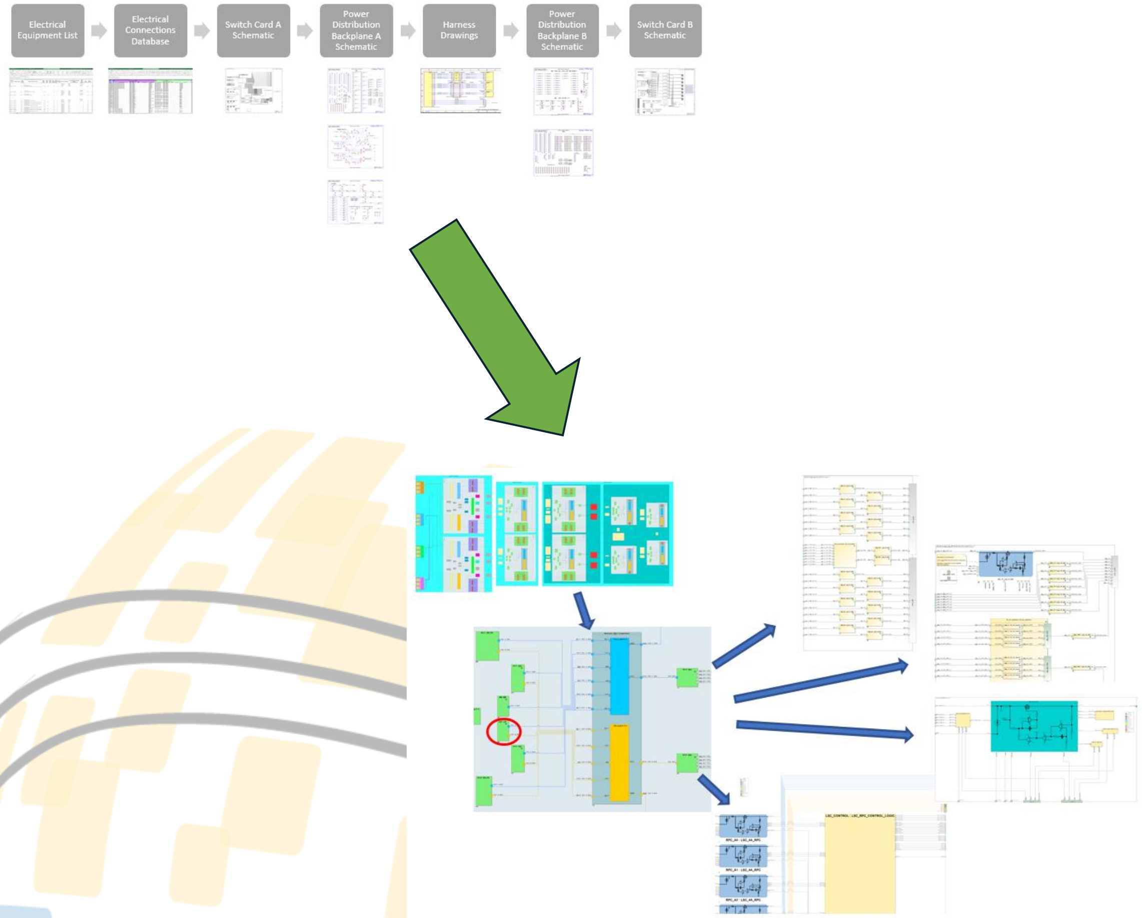
#	Drawing Number	Cage Code	Rev	Name	URL
1	SMPL12300	77573	-	CM Electrical Checkout Diagram	https://nasa-ice.
2	SMPL12301	77573	A	Printed Wiring Assembly And Schematic - Load	https://nasa-ice.
3	SMPL12302	77573	C	Printed Wiring Assembly And Schematic, Umbil	https://nasa-ice.
4	SMPL12303	77573	B	Schematic Diagram - Power Controller	https://nasa-ice.
5	SMPL12304	7757			
6	SMPL12305				
7	SMPL12306				
8	SMPL12307				
9	SMPL12308		D	Schematic Diagram, Battery Charge Controller	https://nasa-ice.
10	SMPL12310		A	Schematic Diagram, Crew Module Propulsion	https://nasa-ice.
11	SMPL12311				
12	SMPL12312			Schematic Diagram, Internal Power Supply	https://nasa-ice.
13	SMPL12313			Schematic Diagram, Event Controller	
14	SMPL12314	77573	-	Schematic Diagram, Solenoid Drive Output	https://nasa-ice.

Document Revision Traceability to Model Elements

- Keep track of latest source document revisions
- Scope out necessary changes to SysML model

Source of Truth

Lessons Learned: Artifact Navigation



- Demonstrated the value of co-located dynamically navigable information using Cameo Collaborator.
- Document-centric status quo involves traversal of hundreds of disjoint documents, spreadsheets, and drawings.
  - Process is time-consuming and error-prone.
- The interconnected nature of an SysML model can be leveraged reduces system traversal to simple and intuitive clicks.
- “The ability to view from a high-level down to the schematic was way faster compared to the alternative of finding a schematic in PDFs.”

Lessons Learned: Human Error Reduction

During the course of developing the Orion Digital Twin, errors were discovered in the source design baselined material (thus demonstrating the value of systems modeling inherent to SysML with a real-world example) including but not limited to:

- Solar Panel parameters within design document had mismatched columns.
- Discrepancies between pages within electrical checkout diagrams between physical wire pin-in pin-out mates.
- Appearance of copy-and-paste signal designators lacking necessary changes within new context.
- Signals labeled as ground on both power and return interfaces.
- Inconsistent updates to design changes within a single document.

Lessons Learned: Parametric Equation Solving

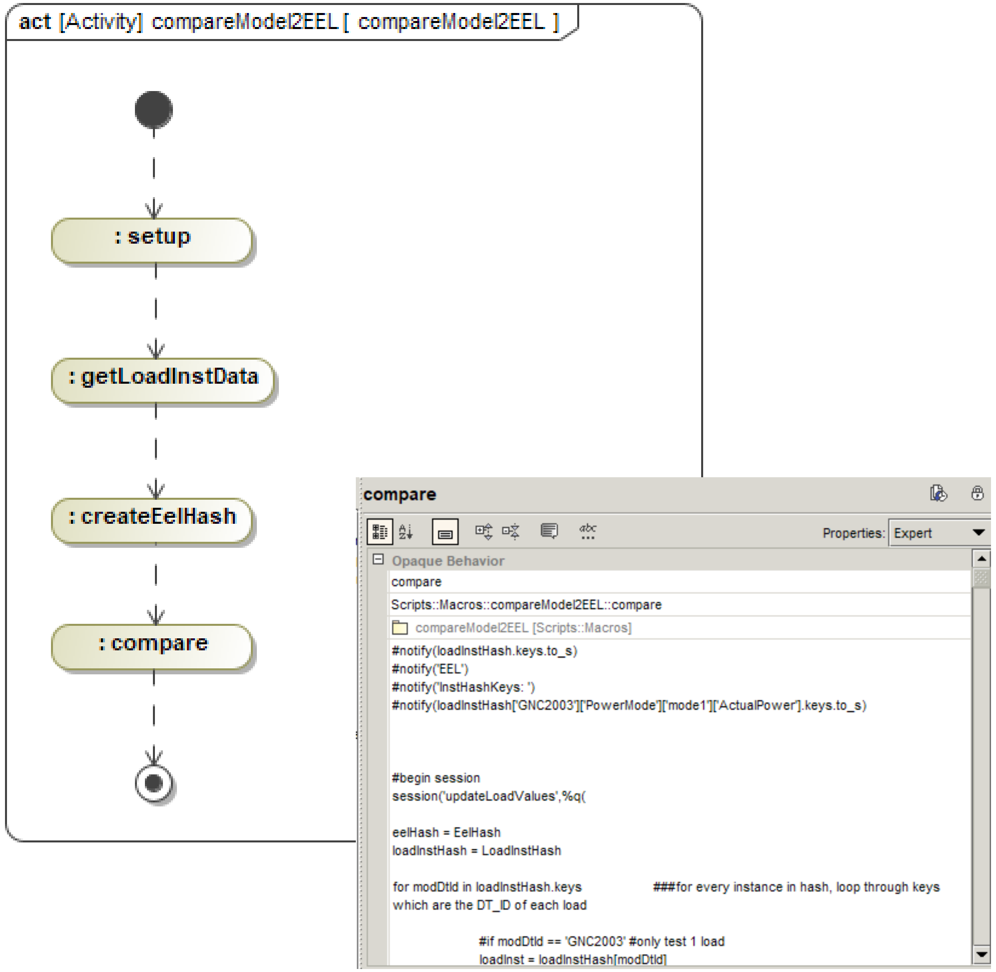
- Deconflicting human-readable diagrams and MagicDraw Equation solving
  - Modeling the system vs modeling the simulation
  - Flow direction vs flow property arrows and Cameo Sim Toolkit (CST) value propagation
  - Compromise were multiple layers to provide both capabilities

- Functional Mock-up Unit (FMU) Integration
  - CST can struggle with solving complex systems of equations
  - CST updates values changes individually until the last variable settles-out. This can result in convergence, divergence to arbitrarily large numbers, or pivot around a pseudo-stability point.
  - Issues can be resolved by encapsulating executable model elements within a single FMU, which can provide:
    - Bounds to acceptable resting variable values within a single time-step
    - Delays to inputs within a loop
    - Aiding the looping iteration by introducing virtual control mechanisms such as damping

- MATLAB Integration
  - Integration of simple MATLAB scripts in heavily re-used model elements caused considerable performance impacts
  - CST will only use a single MATLAB process
  - A potential work around is passing a single matrix of values to be processed by MATLAB within a single timestep
  - Gains in simulation performance are offset by loss of component re-use and manual creation of extra MATLAB-SysML interfaces

Lessons Learned: In-Model Scripting with Opaque Behaviors

- The automation scripts used to create and maintain the SysML structural elements from parsable authoritative sources were developed, organized, and implemented within the model itself.
- Generic tables provided a convenient presentation of the reusable scripts captured in SysML opaque behaviors which could then be dragged-and-dropped onto activity diagrams to develop more complex algorithms.
- Cameo Simulation Toolkit can execute those activity diagrams running the scripts to perform the model manipulation needed to first generate and then maintain the synching of the digital twin model to changing source data.



Twininess

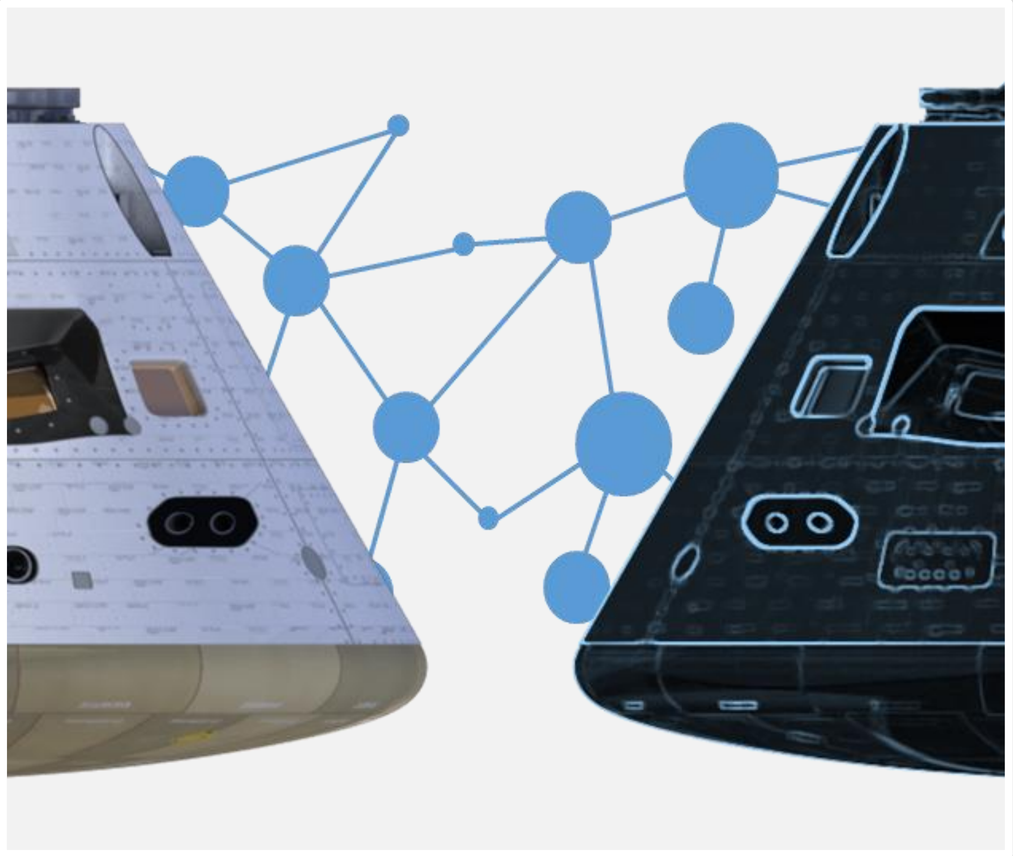
The extent, by both scope and degree, a system model is a digital twin.

Characterizes

- Nature of the connections to the physical system
- Level of autonomy
- Frequency of synchronization
- Fidelity of the model

Considers

- Use cases
- System Characteristics
- Capabilities



Digital Twin – Fingerprint

Use Cases

- Configuration Insight
- Performance Simulation
- Design Optimization
- Performance Forecasting
- Failure Effect Discovery

System Characteristics

- Class & Criticality
- Scale
- Domain

Capabilities

- Data Services
- Integration
- Intelligence
- User Experience

Digital Twin - Use Cases

As Designed

- Calibration / Articulation
- Simulated Performance Analysis
- Virtual Requirement Validation
- Simulated Requirement Verification
- Architecture / Design Optimization
- Market Gap Analysis & Capabilities

As Built

- Nonconformance Analysis
- Sustainment/ Maintenance
- Modifications
- Manufacturing Performance
- Material Certifications

As Tested

- Product Variation
- Sub-Performance Identification
- Qualification Unit Certification
- Known Failure Scenario Operations Plan

As Operated

- Degradation Analysis / Performance Forecasting
- Need for Repair Notification
- Learned Performance Optimization
- Inform Operational Decision Trades
- Learned Control Algorithm Optimization
- Informed Replacement Preparation
- Sensor-Elusive Failure Modes
- Root Cause Analysis
- Downstream Failure Effect Analysis
- Failure Prediction
- Sensor/Telemetry Integrity Sentinel

Explored Attribute

Use Cases were derived from AIAA DEIC 2020 Position Paper on Digital Twins

Digital Twin – System Characteristics

System Type
- Human Spaceflight
- Aircraft
- Satellite
- Rover

Mission Context
- Earth Atmosphere
- Earth Orbit
- Moon Orbit
- Moon Surface
- Deep Space

Asset Multiplicity
- Singular unit
- Repeated components / assemblies
- Fleet of Systems

Domain
- Structures
- Thermal
- C&DH
- C&T
- ECLS
- GN&C
- Propulsion
- EPS

Simulation / Analysis Complexity
- Single Domain
- Multi-Domain

Lifecycle Stage Application
- Mission Design
- System Design
- Manufac-turing
- Test
- Operations

Twin Scope/ Fidelity
- Nuts/bolts
- Component
- Part
- Assembly
- Discipline
- Subsystem
- System
- System of Systems

Project Involvement
- Pilot
- Prototype
- Parallel
- Critical Path

Data Thread Complexity
- Low
- Moderate
- High

Mission Certification / Class
- A
- B
- C
- D

Team Size
- 1-3
- 4-6
- 7-10

Center Collabor-ation
- 1 Center
- 2 Centers
- 3+ Centers

Explored Attribute

Digital Twin - Capabilities

- The required enabling capabilities vary significantly based on system characteristics and desired digital twin applications
- The Digital Twin Consortium has defined 62 capabilities in their “Capabilities Periodic Table”
- The Orion Digital Twin relies most heavily on:

Data Acquisition & Ingestion	Data Transformation	Data Contextualization	Data Aggregation	Digital Twin Integration
Collab Platform Integration	API Services	Simulation	Composition	Basic Visualization
		Security		

Legend: Data Services | Integration | Intelligence | User Experience | Management | Trustworthiness

Forward Work Candidates

- Mission Certification for Artemis II
- Orion Subsystems
  - Co-simulation of subsystems
  - Full application of approach to Artemis–III Orion vehicles
- Enhanced Twininess
  - Mission systems integration
  - Pause-and-Play capability
- Requirement Traceability
  - Trace model constraints to requirements in the ASOT
- Operational Data Systems Integration
  - Discrepancy reports
  - Acceptance and lot testing
  - Hardware scans
- Volumetric Model Integration
  - 3D CAD integration/interface
  - Metaverse integration
- Learned Fault Recognition Prediction
  - Identify markers that could lead to co-morbid faults – AI/ML
- Enhanced Simulation Capabilities
  - Integration with mission environment sim
  - Multi-domain simulation

Orion Digital Twin Summary

Initial development of the Orion EPS Digital Twin is complete and was ready to assist in mission support activities for the Artemis 1 mission.

- It demonstrated that:
  - A detailed digital twin system model can be created and maintained late in the development lifecycle, in addition to provide design insight in support of flight operations.
  - Aggregating as-designed, as-built, as-tested, and as-operated data can provide insights not possible using traditional document-based approaches.
  - The time needed to answer critical questions is reduced by orders of magnitude.
  - MBSE's promise of efficiency through reuse is valid, having represented over 9000 components with only 600 definition elements in the model.

- Agency-wide Impacts
  - Building-blocks have jump-started new or enhanced modeling efforts by major NASA programs and projects.
  - Has inspired and emboldened projects within NASA to undertake system architecture modeling, MBSE-based simulation, and digital twin development as it is now a proven, efficient, and effective approach to solving NASA's technical challenges.

Questions?

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