End-to-End Example of a Digital Twin

Terry Hill / NASA’s Headquarters' Office of Chief Engineer, Digital Engineering Program Manager

The Keck Institute for Space Studies presents a short course on Digital Twins for Solar System Exploration

Date: November 4, 2024

Bottom Line Up Front (BLUF)

- Digital Twin definition, including models versus digital twins
- Digital Twin benefits over models
- Digital Twin Examples
- Lessons learned, bottlenecks, what not to Digital Twin
- Artificial Intelligence/Machine Learning use within the Digital Twin framework

Why Digitally Transform NASA?

Enduring

Bold

Mission…

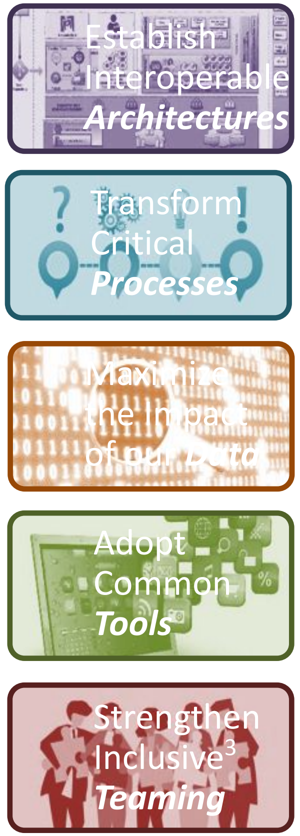
…now in a Changing World

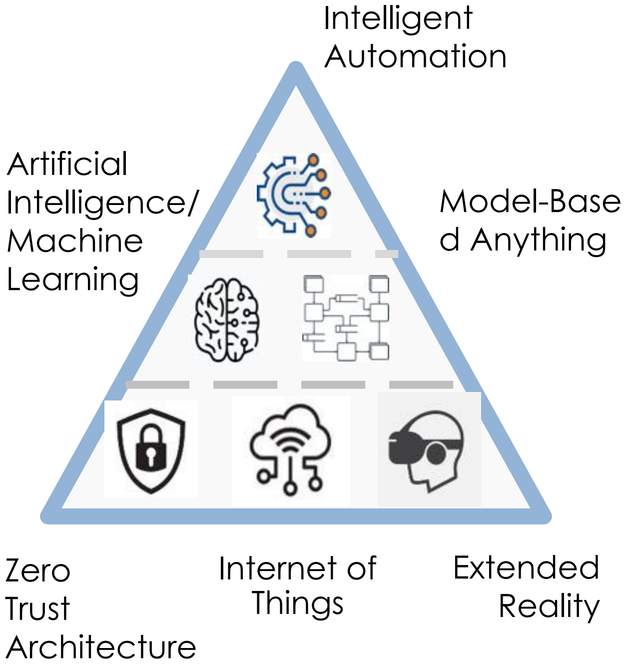
Increasingly bold & complex missions
Increasingly partnered
Increasingly fast
Increasingly affordable
Increasingly transparent
Increasingly inclusive

NASA DIGITAL TRANSFORMATION

NASA's DT Strategic Framework

3 FUTURE STATE GOALS **4** TRANSFORMATION TARGETS **5** DIGITAL LEVERS **6** TECHNOLOGY FOUNDATIONS **7+** MISSION OUTCOMES





One Future NASA

NASA TM 20220018538

WHAT IN THE WORLD IS A DIGITAL TWIN?!?

Does a Digital Twin By Any Other Name Smell Just as Sweet?

- **DoDI 5000.97:** "A digital twin is a virtual representation of a product, system, or process that uses the best available models, sensor information, data collected from the physical system, and input data to mirror and predict system activities and performance over the life of its corresponding physical twin and inform system design changes over time. There can be multiple digital twins of a system, but all digital twins should be based on authoritative sources of information and have clearly defined uses and scopes. Digital twins may vary in fidelity, based on the use case."
- **Digital Twin Consortium (DTC) 2022:** "A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity." https://www.digitaltwinconsortium.org/hot-topics/the-definition-of-a-digital-twin.htm
- ***Digital Twin: Definition & Value* – AIAA and AIA, December 2020:** "A Digital Twin is a virtual representation of a connected physical asset." https://www.aiaa.org/docs/default-source/uploadedfiles/issues-and-advocacy/policy-papers/digital-twin-institute-position-paper-(december-2020).pdf
- **IBM *How does a digital twin work?*:** "A digital twin is a virtual model designed to accurately reflect a physical object. The object being studied — for example, a wind turbine — is outfitted with various sensors related to vital areas of functionality. These sensors produce data about different aspects of the physical object's performance, such as energy output, temperature, weather conditions and more. This data is then relayed to a processing system and applied to the digital copy." https://www.ibm.com/topics/what-is-a-digital-twin

- **NNSA definition:**
  - Digital Twin is a set of virtual information constructs that mimics the structure, context and behavior of an individual / unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value.*
  - Essential elements of a Digital Twin:
    - a virtual representation (digital model)
    - a physical realization (asset)
    - a transfer of data / information (connected) between the two
  - A Digital Twin encompasses the entire product lifecycle of a physical asset, i.e. the design and engineering phase ("As Designed"), the manufacturing phase ("As Built"), and the operational/sustainment phase ("As Used" and "As Maintained"), whenever a physical asset is employed.
- **National Academies, Sciences Engineering Medicine**, *Foundational Research Gaps and Future Direction for Digital Twins*, Dec. 2023: "A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.

Does a Digital Twin By Any Other Name Smell Just as Sweet?

Digital Twin Consortium (DTC) 2022:
https://www.digitaltwinconsortium.org/hot-topics/the-definition-of-a-digital-twin.htm

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

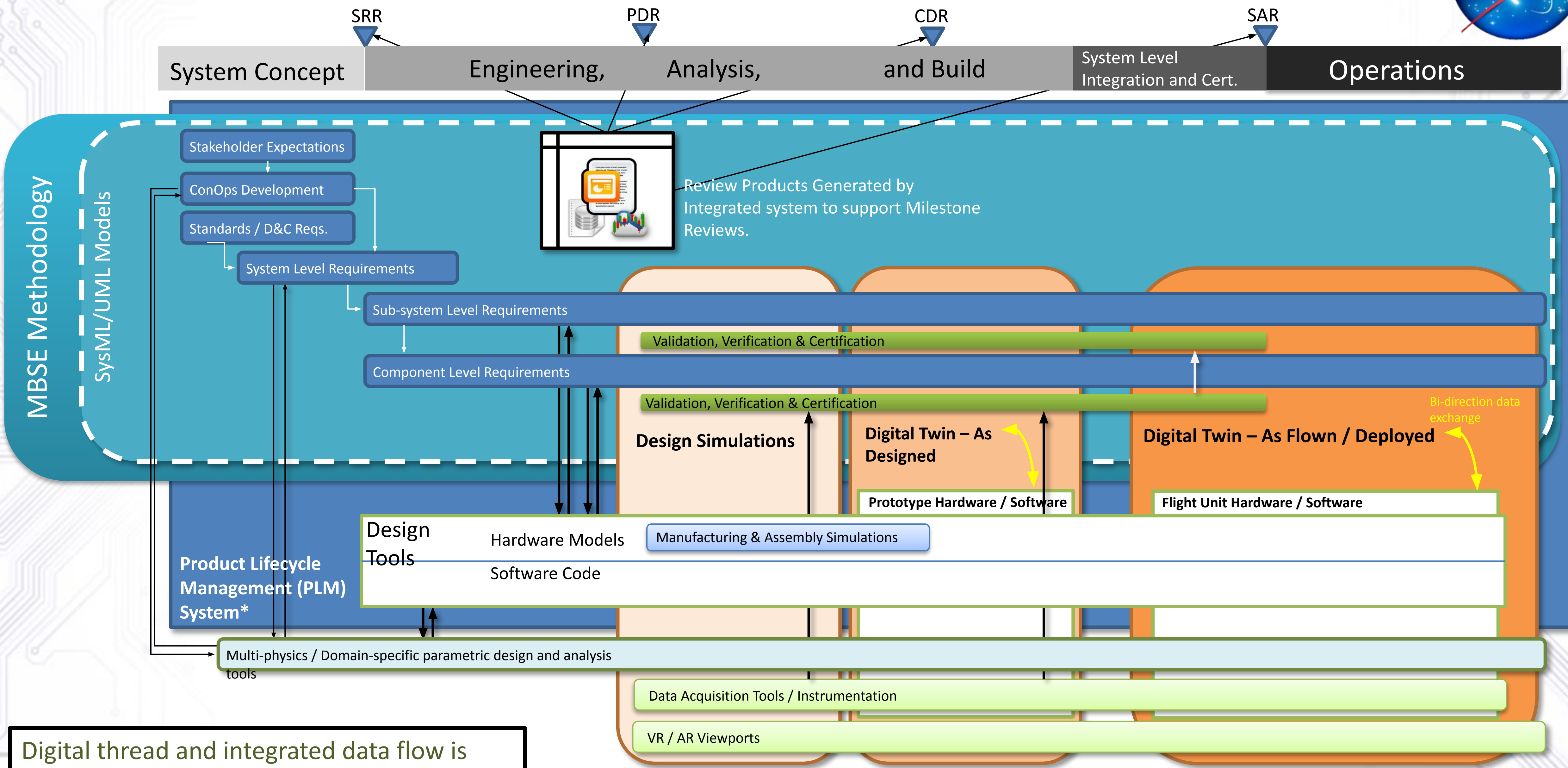
- Digital twin systems transform business by accelerating holistic understanding, optimal decision-making, and effective action.
- Digital twins use real-time and historical data to represent the past and present and simulate predicted futures.
- Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems.
- The foundational elements of the definition are captured in the first sentence: the virtual representation, the real-world entities and processes it represents, and the mechanism by which the virtual and real-world entities are synchronized

Common to all definitions:

- A virtual representation of a product/object, system, process/behavior of something in the physical/natural world
- Data is exchanged between virtual and physical systems.

So yes, it generally does smell just as sweet!

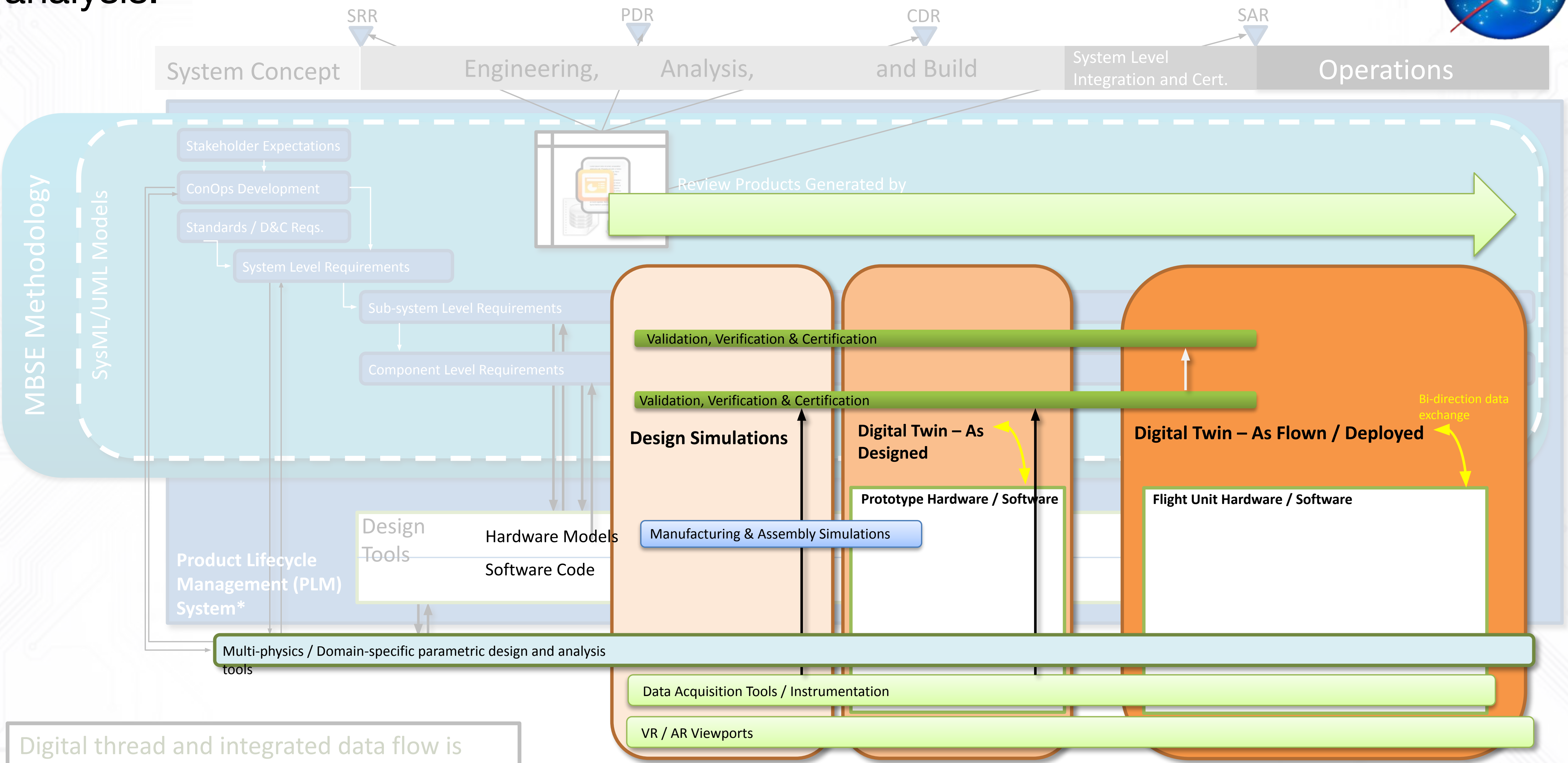
Integrated Digital Engineering Framework per Lifecycle of a Project and how Digital Twins can Evolve out of Standard Development of Engineering Models



Digital thread and integrated data flow is represented via arrows

* Some PLM systems may integrate with multi-physics tools and/or store analysis results.

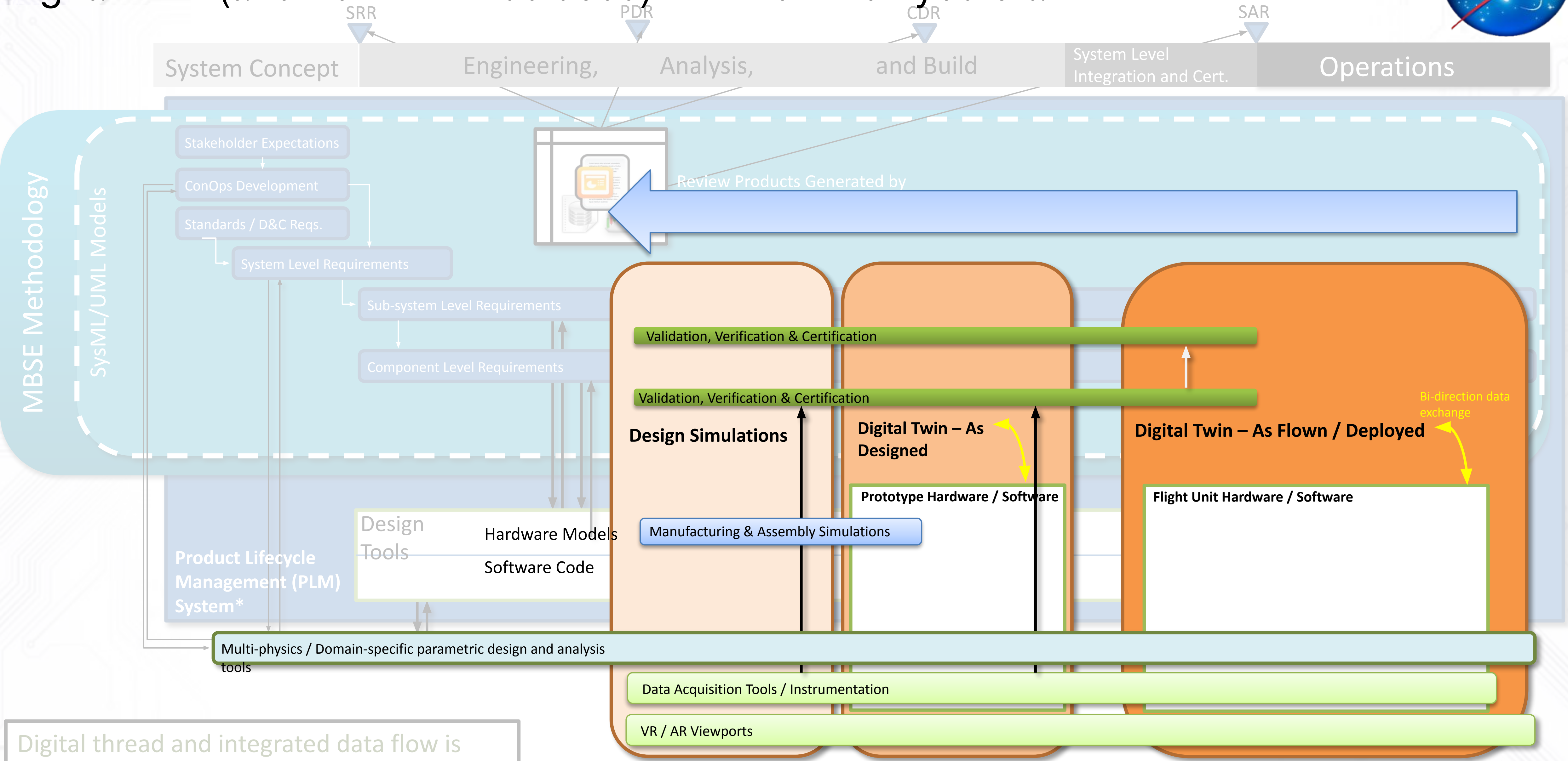
Digital Twins can & should be and evolution of the models used for design and analysis.



Digital thread and integrated data flow is represented via arrows

* Some PLM systems may integrate with multi-physics tools and/or store analysis results.

… But only if you build, integrate, and certify the models with the well-scoped Digital Twin (and how it will be used) in mind when you start.



Digital thread and integrated data flow is represented via arrows

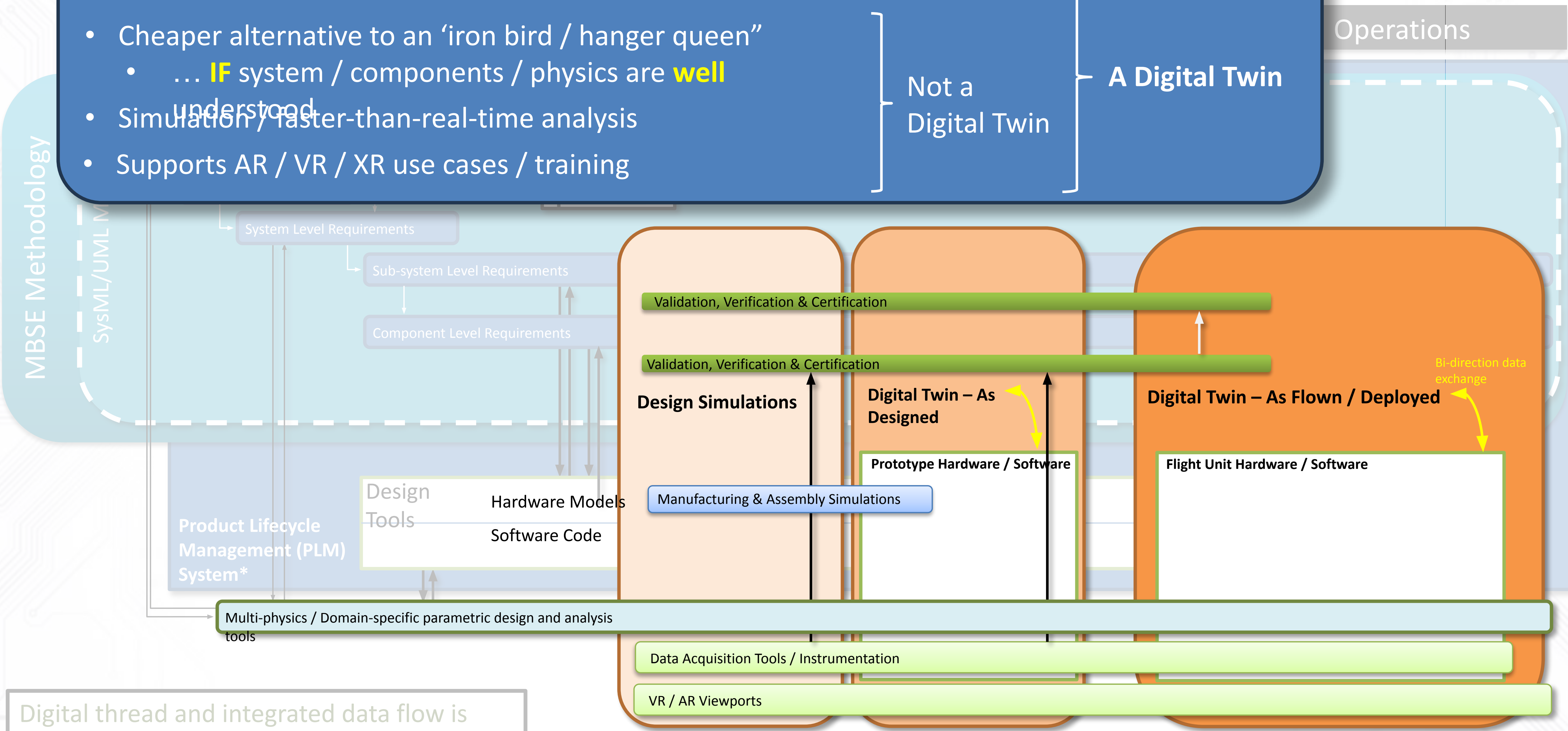
* Some PLM systems may integrate with multi-physics tools and/or store analysis results.

Benefits of Digital Twins

- Bi-directional data interaction with real-world asset
- Cheaper alternative to an ‘iron bird / hanger queen”
  - … **IF** system / components / physics are **well** understood
- Simulation / faster-than-real-time analysis
- Supports AR / VR / XR use cases / training

Not a Digital Twin

A Digital Twin



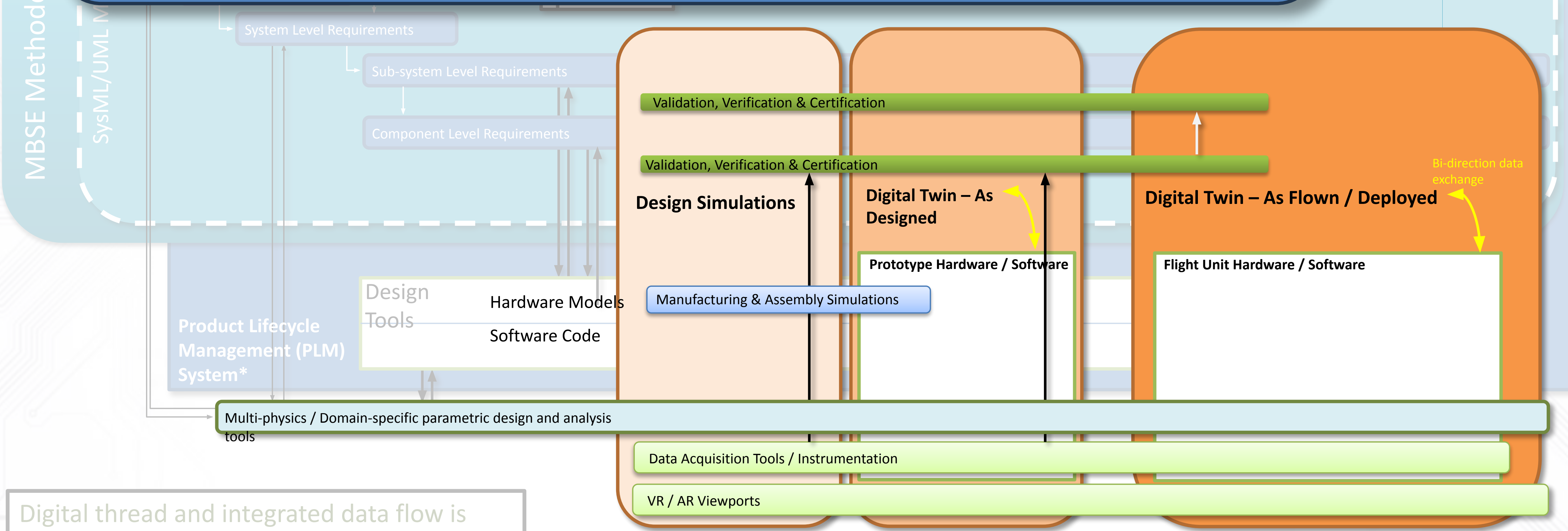
Digital thread and integrated data flow is represented via arrows

* Some PLM systems may integrate with multi-physics tools and/or store analysis results.

Things to Consider Before Creating Digital Twins

- Bi-directional data interaction with real-world asset ← What is my ROI & is it worth it?
- Cheaper alternative to an ‘iron bird / hanger queen” ← “All models are wrong, but some are useful.” – George Box
  - … **IF** system / components / physics are **well** understood
- Simulation / faster-than-real-time analysis
- Supports AR / VR / XR use cases / training

Is the risk of being wrong well understood & worth it?



Digital thread and integrated data flow is represented via arrows

* Some PLM systems may integrate with multi-physics tools and/or store analysis results.

Digital Twin - Use Cases

Level 1:

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

NASA Digital Twin Characteristics

Level 2:

System Type
- Human Spaceflight
- Aircraft
- Satellite
- Rover
- Facilities

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
- Manufacturing
- 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 Collaboration
- 1 Center
- 2 Centers
- 3+ Centers

* based on AIAA definition of digital twins

Explored Attribute by NASA

Digital Twin - Capabilities

- The required enabling capabilities vary significantly based on system characteristics and desired digital twin applications
- The Digital Twin Consortium has defined the following capabilities in their “Capabilities Periodic Table”

1 Data Acquisition & Ingestion	9 Synthetic Data Generation	17 Enterprise System Integration	23 Edge AI & Intelligence	29 Prediction		39 Basic Visualization	45 Dashboards
2 Data Streaming	10 Ontology Management	18 Eng. System Integration	24 Command & Control	30 Machine Learning ML		40 Advanced Visualization	46 Continuous Intelligence
3 Data Transformation	11 Digital Twin (DT) Model Repository	19 OT/IoT System Integration	25 Orchestration	31 Artificial Intelligence AI	35 Prescriptive Recommendations	41 Real-time Monitoring	47 Business Intelligence
4 Data Contextualization	12 DT Instance Repository	20 Digital Twin Integration	26 Alerts & Notifications	32 Federated Learning	36 Business Rules	42 Entity Relationship Visualization	48 BPM & Workflow
5 Batch Processing	13 Temporal Data Store	21 Collab Platform Integration	27 Reporting	33 Simulation	37 Distributed Ledger & Smart Contracts	43 Augmented Reality AR	49 Gaming Engine Visualization
6 Real-time Processing	14 Data Storage & Archive Services	22 API Services	28 Data Analysis & Analytics	34 Mathematical Analytics	38 Composition	44 Virtual Reality VR	50 3D Rendering
7 Data PubSub Push	15 Simulation Model Repository	52 Device Management	54 Event Logging	56 Data Encryption	58 Security	60 Safety	51 Gamification
8 Data Aggregation	16 AI Model Repository	53 System Monitoring	54 Data Governance	57 Device Security	59 Privacy	61 Reliability	62 Resilience

Data Services Integration Intelligence UX Management Trustworthiness

Source: www.digitaltwinconsortium.org

Electrical Power System

ORION (ARTEMIS I) DIGITAL TWIN

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.

Digital Twin Ecosystem

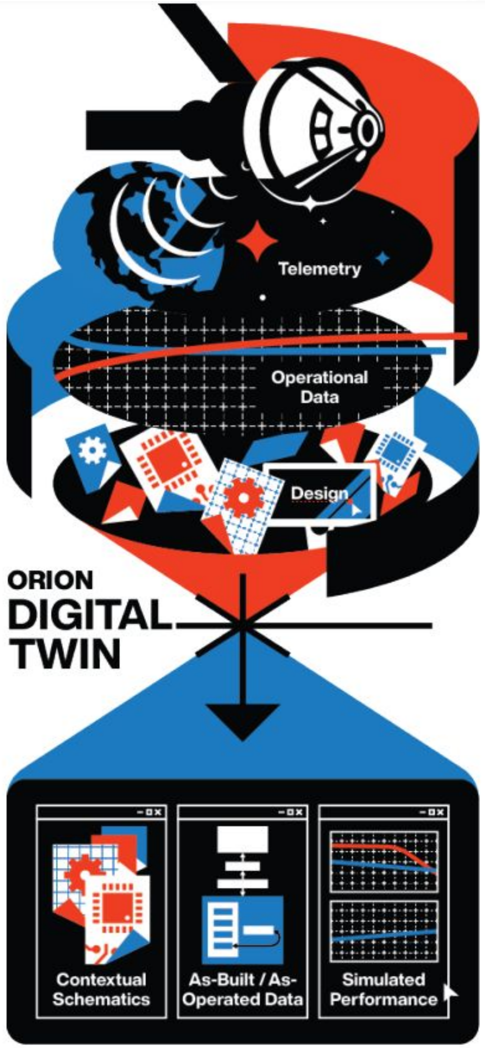
Twofold project goals:

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

- Utilize system modeling tool MagicDraw to create a SysML model foundation for a digital twin of Orion systems that is able to provide needed insight to the operations and engineering teams. This includes:
  - Detail - and context-rich schematics
  - Web-accessibility in a COTS tool
  - System-level simulations
  - As-designed/As-tested/As-operated unit-specific data

- Development will begin 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.

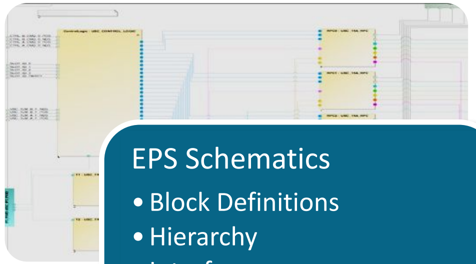
- Development could also proceed with the support of additional digital twin integration and simulation use cases.

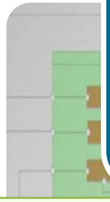
Orion Digital Twin Project 2021-2022 Activities

FY2021 | 2022

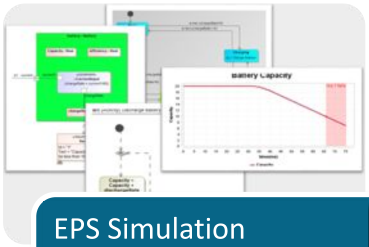
March | April | May | June | July | August | September | October | November | December | January | February | March | April | May | June | July | August | September

Development
- Prototype
- Depth Trade
- Domain Research





EPS Schematics
- Block Definitions
- Hierarchy
- Interfaces
- Schematic Integration
- June – Board interfaces & "Switch" details
- July – Loads
- Aug+ - Board internals



EPS Simulation
- Define Sim Scenario
- Define behavior model
- Develop GUI for live mission scenario

EPS Twin Integration
- Telemetry Interface
- Operational Data Interface
- Parameter Definition

Artemis I Test Case
- Feedback from live mission use by EPS engineering team

EPS Digital Twin Validation/Evaluation
- Model-Based Review
- Live Reviews
- Automated Audits

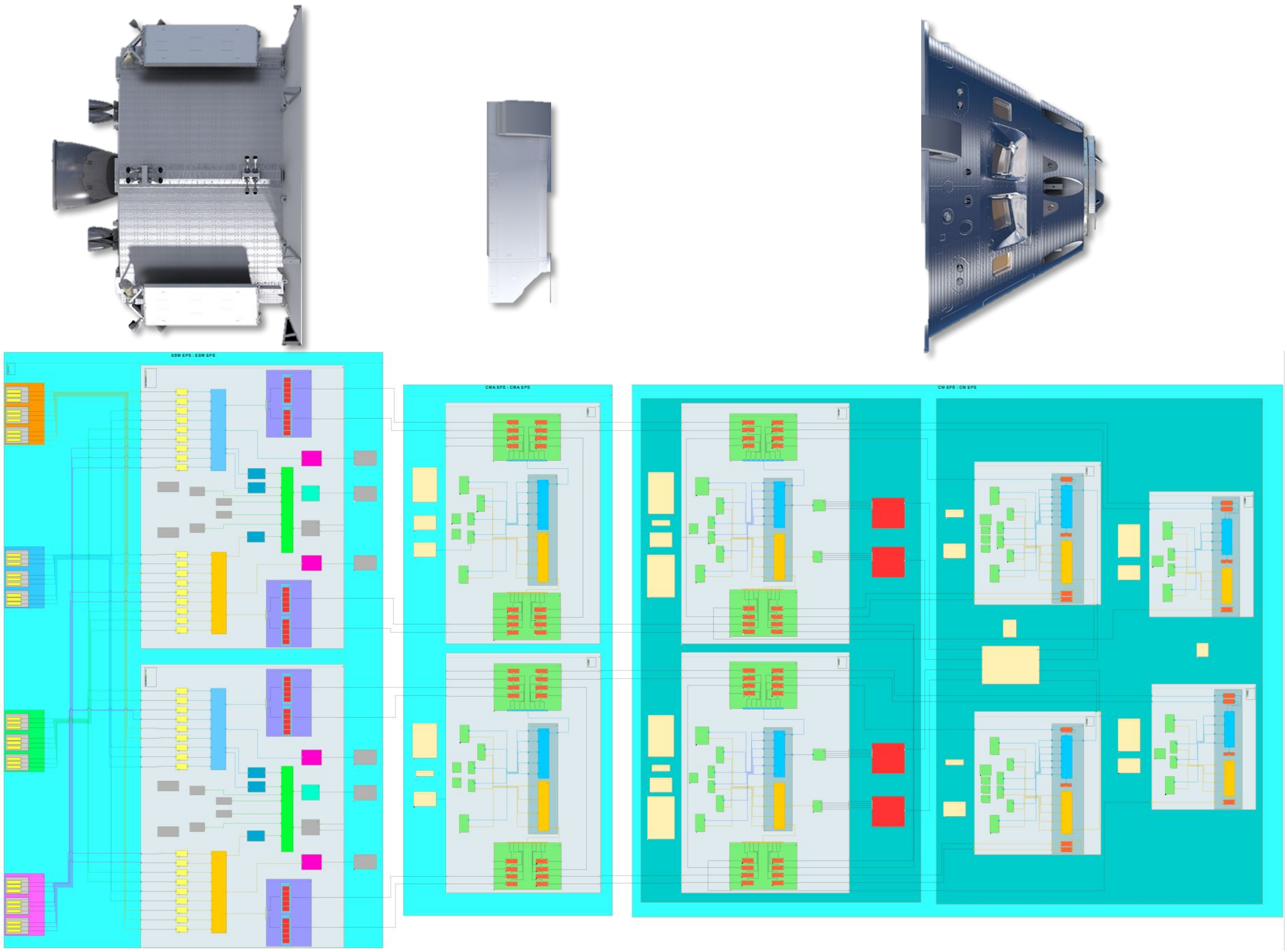
Further Subsystem Development
- Multi-Domain Simulation
- Tool Integration
- Comprehensive Digital Twin Framework

Package for Agency Wide Use
- Lessons Learned
- Sanitized Model
- Script Library
- Reusable Components

- 10 months of modeling and 8 months of validation.
- Over 9,000 components represented
- ~6000 elements of definition reused
- Over 130 hyperlinks to schematics database integrated into SysML Model
- Over 4,500 interfaces defined between components
- 2,208 ports imported ready for CD&H/Avionics/GNC subsystems
- Over 500 loads integrated into EPS architecture
- Automated syncing and validation of data and architecture to authoritative sources
- Simulation utilizing built architecture and imported component specifications

2023 INCOSE IS Best Paper in Mod/Sim Category

Orion EPS Architecture

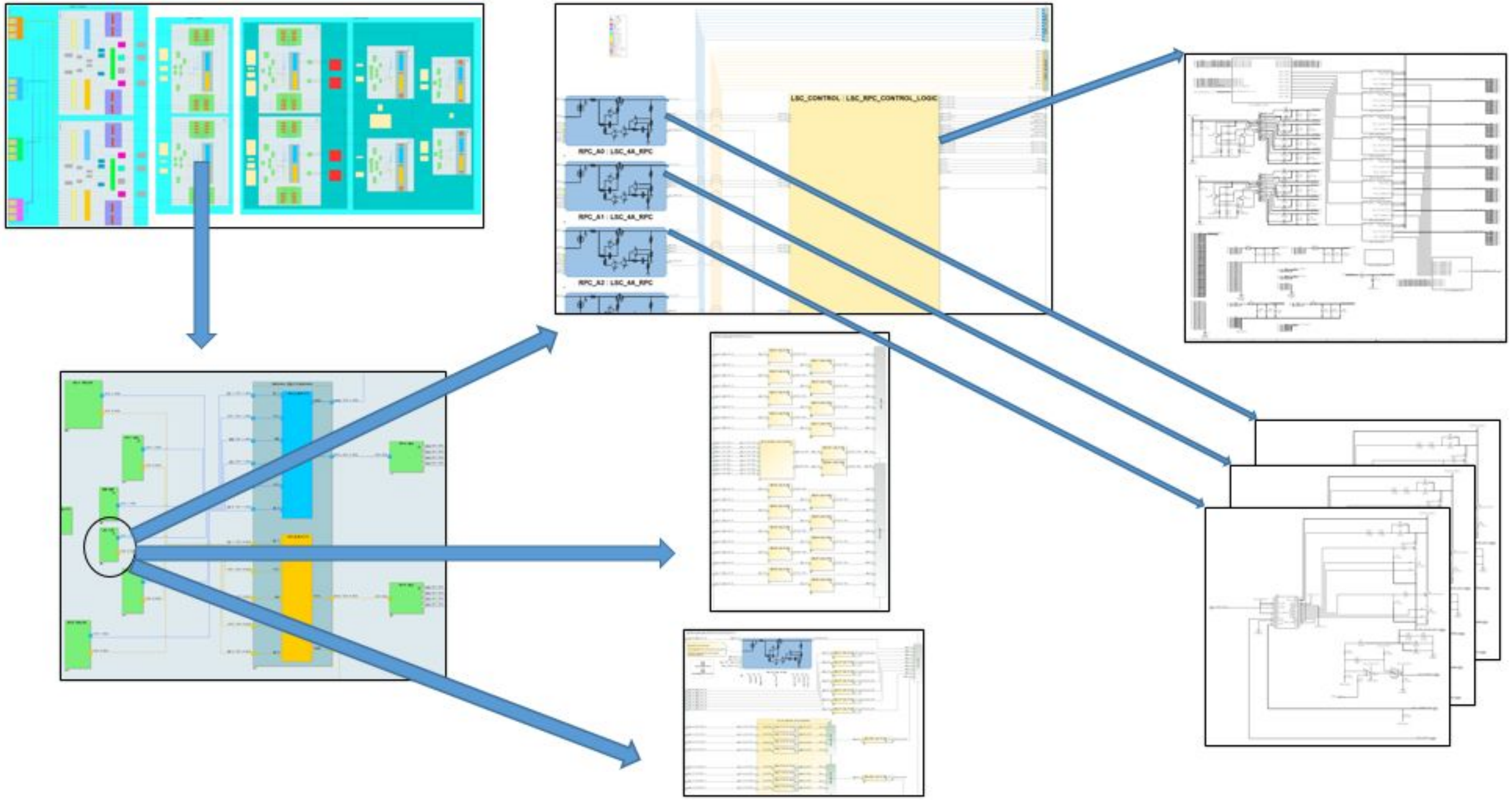


Integrated Schematics

Component Breakdown

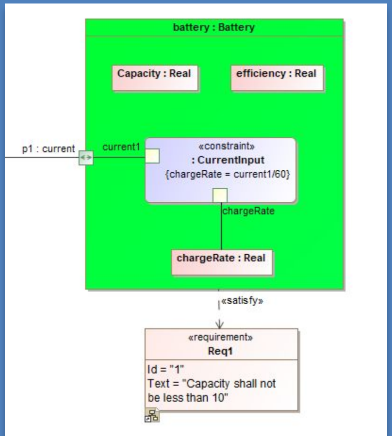
Curated Views

Hyperlinked to Manufacturing Schematic Database

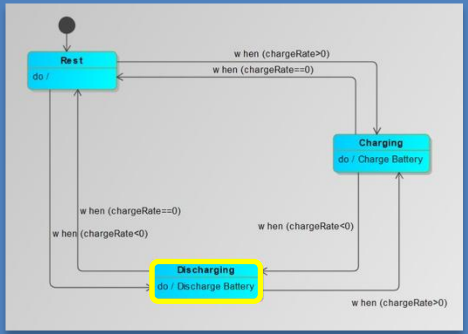


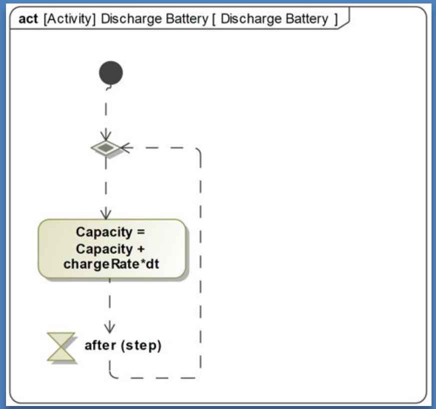
Integrated Simulation

- Interfaces
- Key Parameters
- Mathematical Relationships
- Requirements

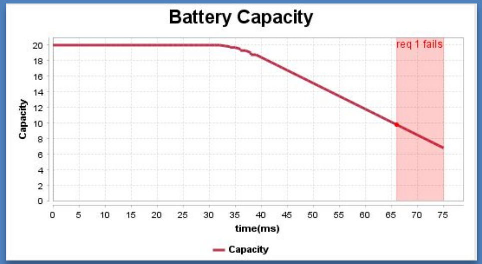


- Component Behavior

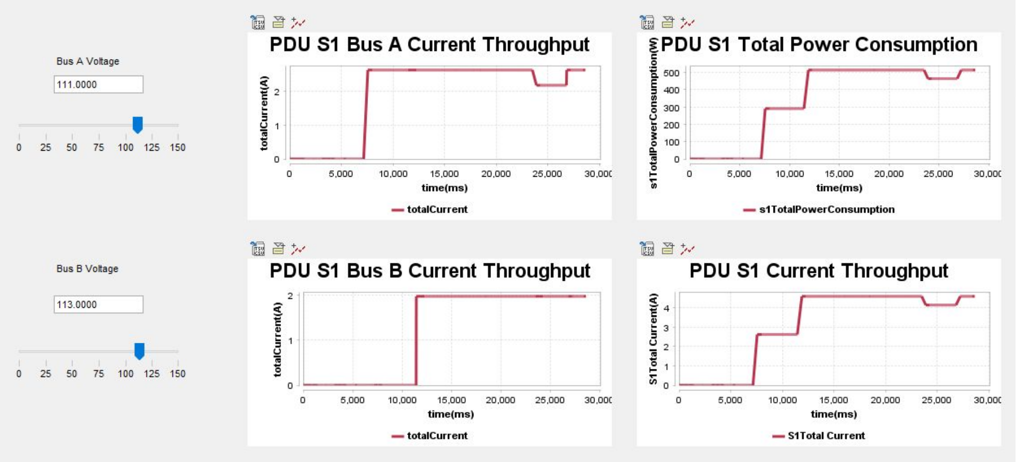




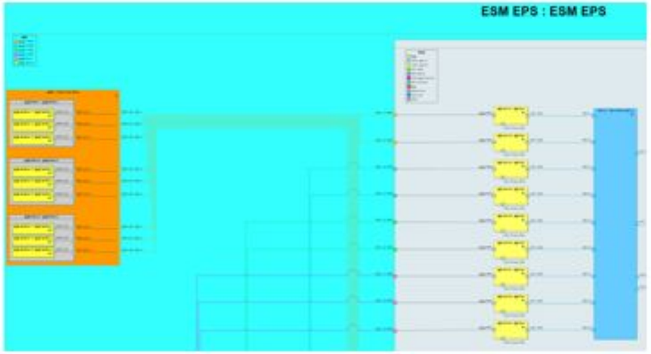
- Performance Analysis
- Verification of Requirements

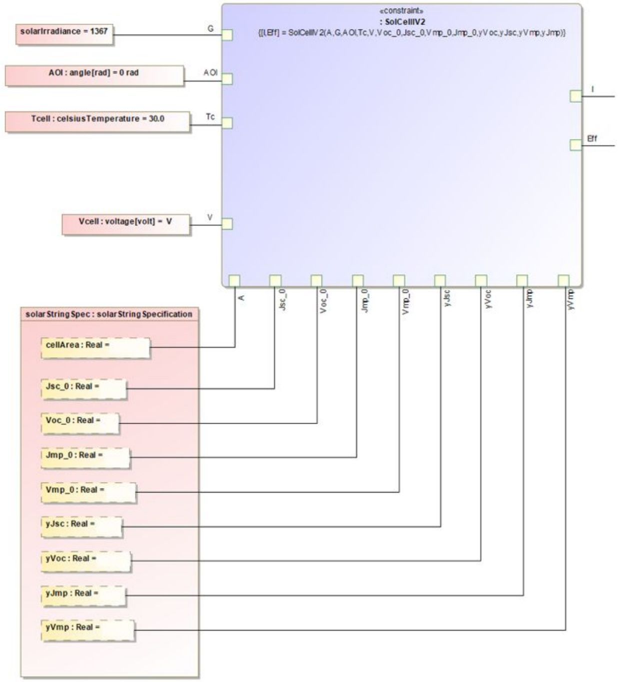


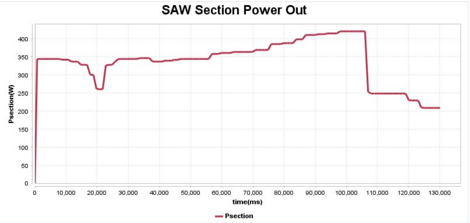
Integrated Simulation – Power Bus

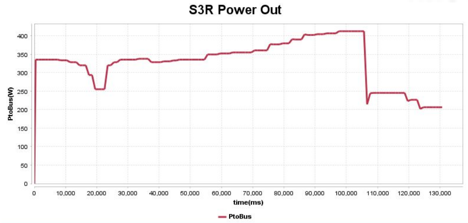


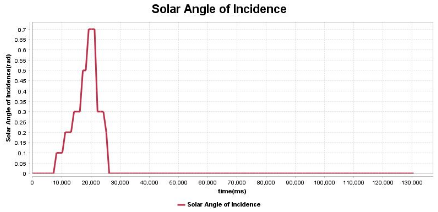
Integrated Simulation – Solar Arrays

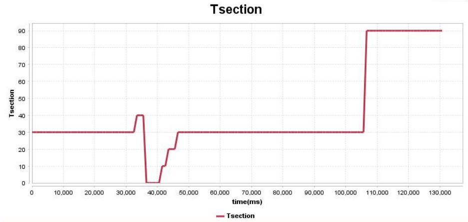


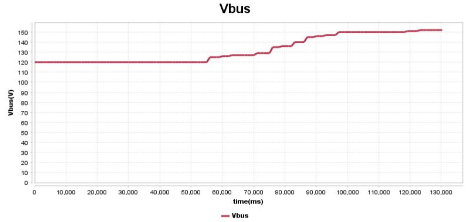




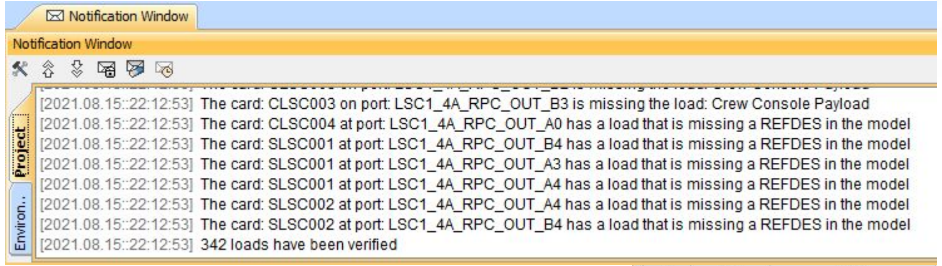








Data Driven Design / Automation

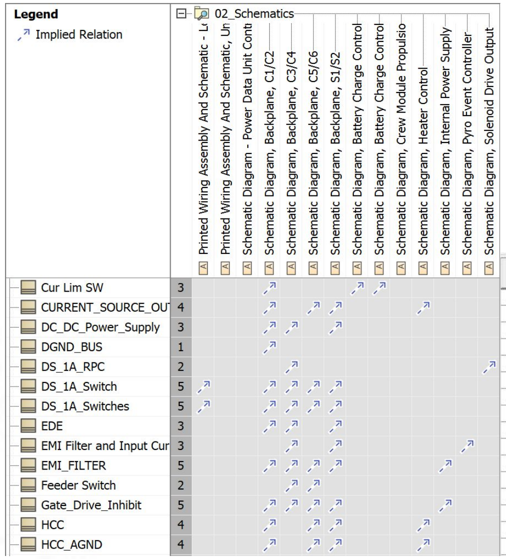


MagicDraw API Automation

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

Document Revision Traceability to Model Elements

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



Name	Drawing Number	Date	Revision	Cage Code
CM Electrical Checkout Diagram	948CN2000012	24/11/20	-	04236
Schematic Diagram, Backplane, S1/S2	948BA1711111	03/10/14	-	04236
Schematic Diagram, Battery Charge Control, Part A	948CA1712311	01/11/16	D	04236
Schematic Diagram, Battery Charge Control, Part B	948CA1712511	01/11/16	B	04236
Schematic Diagram, Backplane, C1/C2	948CA1715111	09/19/14	-	04236
Schematic Diagram, Heater Control	948CA1715311	06/24/14	-	04236
Schematic Diagram, Internal Power Supply	948CA1715511	01/22/15	-	04236
Schematic Diagram, Backplane, C3/C4	948CA1716111	01/12/14	A	04236
Schematic Diagram, Pyro Event Controller	948CA1716211	11/25/14	-	04236
Schematic Diagram, Solenoid Drive Output	948CA1716311	02/25/15	-	04236
Schematic Diagram, Crew Module Propulsion Driver	948CA1716411	01/11/14	A	04236
Schematic Diagram, Backplane, C5/C6	948CA1717111	01/12/14	A	04236
Printed Wiring Assembly And Schematic, Umbilical Switch Car	1722585	06/17/16	C	47PP5
Printed Wiring Assembly And Schematic - Load Swith Card	1722595	11/25/15	A	47PP5
Schematic Diagram - Power Data Unit Controller	8275781	10/23/14	B	61962
ODB Volume II EEL		12/11/21	J	

Source of Truth

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.

Status and Updates

- Orion Artemis I EPS Model is functional and validated
- Artemis I evaluation by EPS system management team

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

- Lessons Learned Captured
  - 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

Another DT Example: Inter-Agency Working Group for Digital Twins for Predicting System Failure

Kicked off in Aug. ‘24

- A Failure Occurred in a System
  - Human Failure
    - Insufficient Training
    - Insufficient Capabilities
    - Insufficient Working conditions
  - Process Failure
    - Process Escape (due to Human)
    - Process Escape (unanticipated operational conditions - Insufficient design)
    - Insufficient Process efficacy monitoring
  - Technical Failure
    - Power
    - Hardware
      - Insufficient Maintenance
        - Insufficient Requirements
        - Process failure
        - Insufficient Funding
      - Normal Wear
        - Insufficient definition of End of Life
      - Insufficient Design
    - Software
      - Insufficient Testing
      - Insufficient Design
    - Network
      - Voice
      - Data

Utilizes a root-cause failure identification approach to determining what the digital twin needs to do and what data is required

Which of these contributors (or others) to a system failure do you want to model with a digital twin?

’Cause you can’t model the universe with a DT.

Digital Twin – Fingerprint

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

System Characteristics

- Class & Criticality
- Scale
- Domain

Capabilities

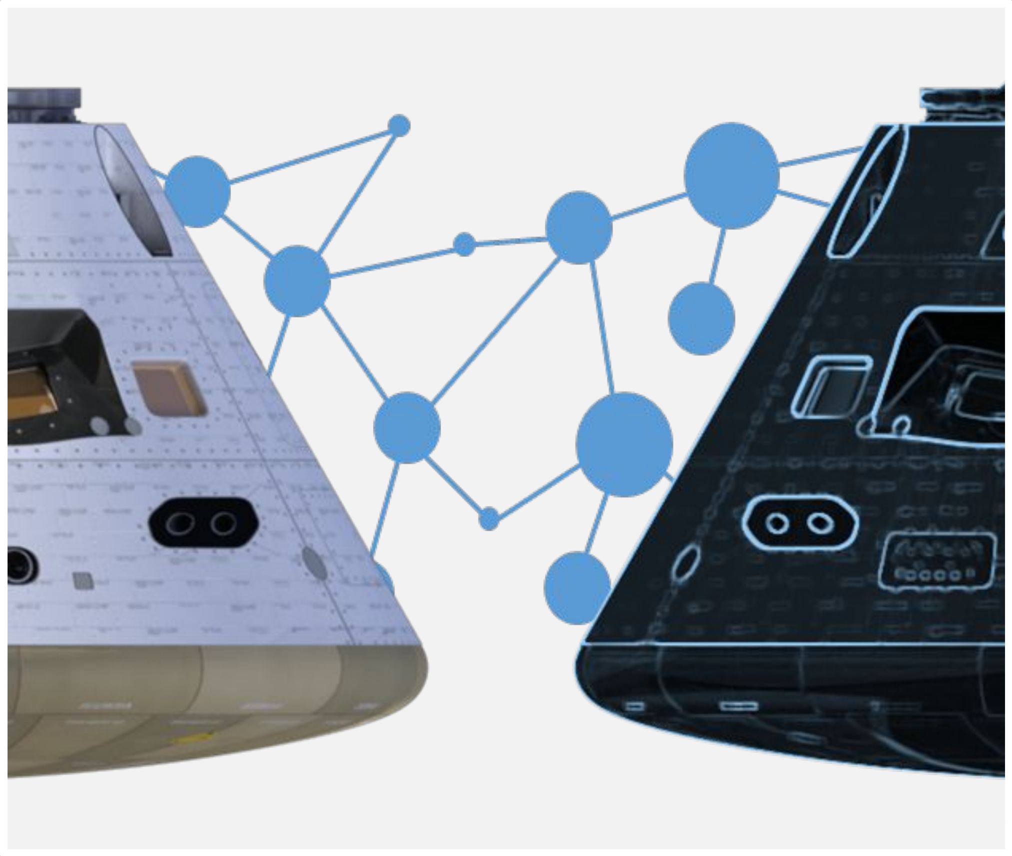
- Data Services
- Integration
- Intelligence
- User Experience

Twininess

The extent, by which 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

Lessons learned, bottlenecks, what not to Digital Twin

Reference Mission: Europa Clipper

Lessons Learned come from *SE Lessons Learned: Europa Clipper*, Ann Devereaux: JPL Division Manager for SEI&T, Richard Kornfeld: JPL Section Manager for Flight Systems, August 2020

Note: This project was pathfinding with the use of MBSE, so being one of the first always means there are lessons to be learned by others. Nothing but respect for this team!

While the Lessons Learned do not pertain specifically to digital twins, they are very relevant given that digital twins are based upon modeling and is a relatively new technology approach much like SysML modeling was for this team.

Europa Clipper: Lessons Learned

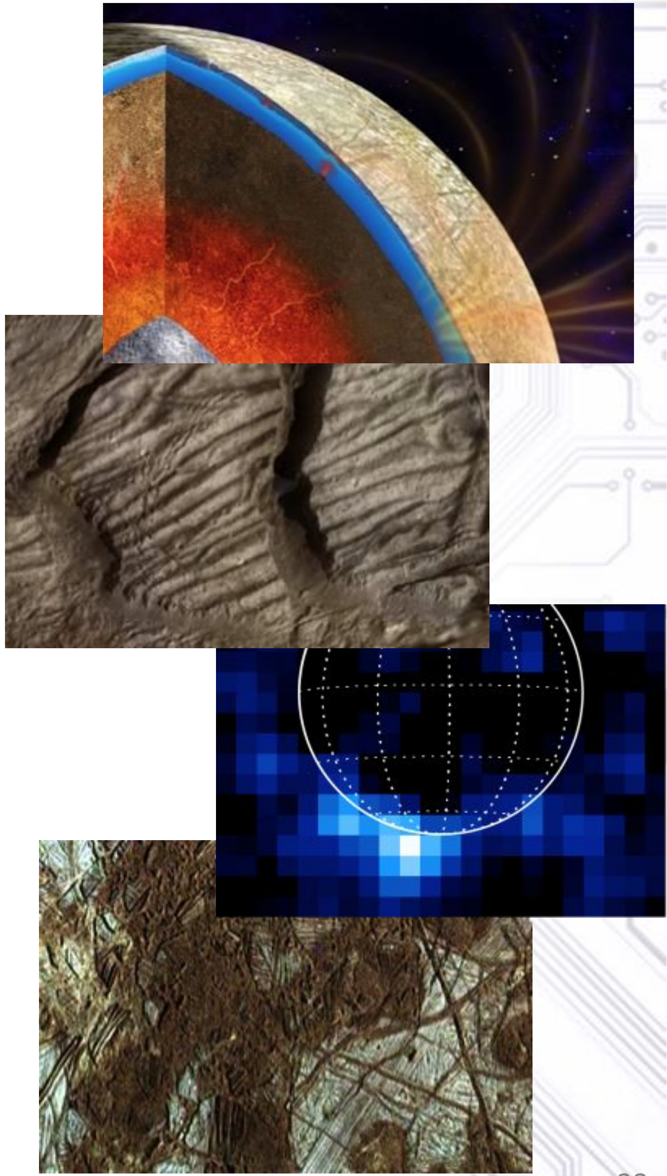
Architectural Framework team attempted to apply same extreme level of rigor to all mission elements, and failed to scale efforts commensurate with relative return on investment for various areas.

The quest to prove “completeness” in architecting, etc. to be achieved via the “mechanization” of the SE function, might not necessarily be justified in all cases; instead, it should be applied judiciously, i.e. where the return on investment warrants it.

Perfect is the enemy of good…

“Striving to better, oft we mar what’s well” – Shakespeare 1606

“Give them the third best to go on with; the second best comes too late, the best never comes.” - Robert Watson-Watt (1892-1973)



Artificial Intelligence and Digital Twins

How should we use Artificial Intelligence in the development of, or use with, digital twins?

Artificial Intelligence and Digital Twins

Suggestions:

Renamed as Augmented Intelligence?

Use it for activities which eat up a lot of human labor time with minimal value?

Use it to help keep track and status of our processes and systems, functionality, and health?

Use it to analyze data / information which is ill suited for humans in a timely manner?

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NASA DIGITAL TRANSFORMATION

Questions?

End-to-End Example of a Digital Twin

Terry Hill / NASA's Headquarters' Office of Chief Engineer, Digital Engineering Program Manager

The Keck Institute for Space Studies presents a short course on Digital Twins for Solar System Exploration

Date: November 4, 2024

Bottom Line Up Front (BLUF)

- Digital Twin definition, including models versus digital twins
- Digital Twin benefits over models
- Digital Twin Examples
- Lessons learned, bottlenecks, what not to Digital Twin
- Artificial Intelligence/Machine Learning use within the Digital Twin framework

Why Digitally Transform NASA?

Enduring
Bold
Mission…

…now in a Changing World

Increasingly bold & complex missions
Increasingly partnered
Increasingly fast
Increasingly affordable
Increasingly transparent
Increasingly inclusive

NASA DIGITAL TRANSFORMATION

NASA's DT Strategic Framework

3 FUTURE STATE GOALS

4 TRANSFORMATION TARGETS

5 DIGITAL LEVERS

6 TECHNOLOGY FOUNDATIONS

7+ MISSION OUTCOMES

Transform the way we Work

Transform the experience of our Workforce

Transform the agility of our Workplace

Establish Interoperable *Architectures*

Transform Critical *Processes*

Maximize the Impact of our Data

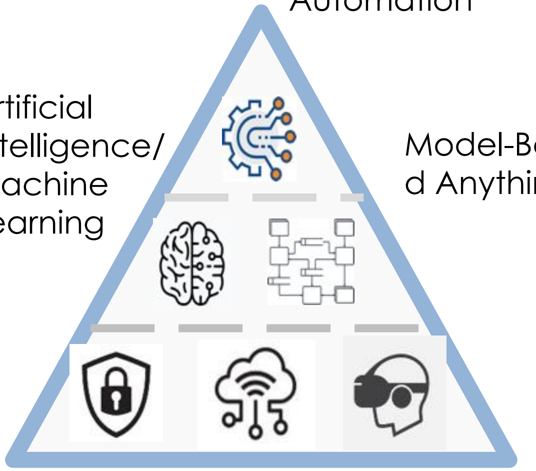
Adopt Common *Tools*

Strengthen Inclusive³ *Teaming*

Intelligent Automation

Artificial Intelligence/ Machine Learning

Model-Based Anything



Zero Trust Architecture

Internet of Things

Extended Reality

Bolder, More Complex Missions

Faster, More Agile Processes

Seamless Partner Teaming

Inspire & Engage Citizens

Affordable Sustainable Operations

Attract & Retain Workforce

Modern Future of Work

One Future NASA

NASA TM 20220018538

Chart cleared for public release Jan 9 2024

WHAT IN THE WORLD IS A DIGITAL TWIN?!?

Does a Digital Twin By Any Other Name Smell Just as Sweet?

- **DoDI 5000.97:** "A digital twin is a virtual representation of a product, system, or process that uses the best available models, sensor information, data collected from the physical system, and input data to mirror and predict system activities and performance over the life of its corresponding physical twin and inform system design changes over time. There can be multiple digital twins of a system, but all digital twins should be based on authoritative sources of information and have clearly defined uses and scopes. Digital twins may vary in fidelity, based on the use case."
- **Digital Twin Consortium (DTC) 2022:** "A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity." https://www.digitaltwinconsortium.org/hot-topics/the-definition-of-a-digital-twin.htm
- ***Digital Twin: Definition & Value* – AIAA and AIA, December 2020:** "A Digital Twin is a virtual representation of a connected physical asset." https://www.aiaa.org/docs/default-source/uploadedfiles/issues-and-advocacy/policy-papers/digital-twin-institute-position-paper-(december-2020).pdf
- **IBM *How does a digital twin work?*:** "A digital twin is a virtual model designed to accurately reflect a physical object. The object being studied — for example, a wind turbine — is outfitted with various sensors related to vital areas of functionality. These sensors produce data about different aspects of the physical object's performance, such as energy output, temperature, weather conditions and more. This data is then relayed to a processing system and applied to the digital copy." https://www.ibm.com/topics/what-is-a-digital-twin

- **NNSA definition:**
  - Digital Twin is a set of virtual information constructs that mimics the structure, context and behavior of an individual / unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value.*
  - Essential elements of a Digital Twin:
    - a virtual representation (digital model)
    - a physical realization (asset)
    - a transfer of data / information (connected) between the two
  - A Digital Twin encompasses the entire product lifecycle of a physical asset, i.e. the design and engineering phase ("As Designed"), the manufacturing phase ("As Built"), and the operational/sustainment phase ("As Used" and "As Maintained"), whenever a physical asset is employed.
- **National Academies, Sciences Engineering Medicine**, *Foundational Research Gaps and Future Direction for Digital Twins*, Dec. 2023: "A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.

Does a Digital Twin By Any Other Name Smell Just as Sweet?

Digital Twin Consortium (DTC) 2022:
https://www.digitaltwinconsortium.org/hot-topics/the-definition-of-a-digital-twin.htm

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

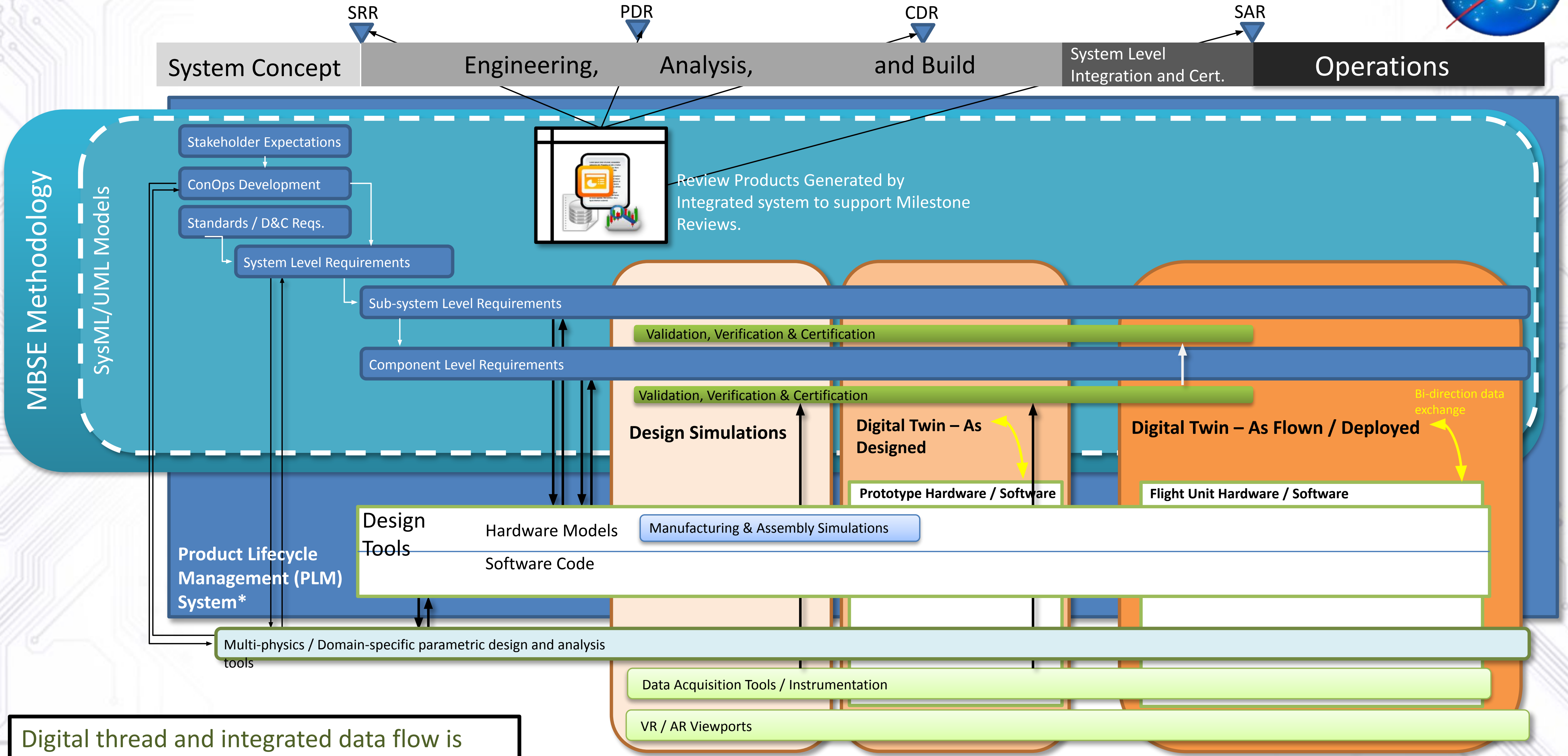
- Digital twin systems transform business by accelerating holistic understanding, optimal decision-making, and effective action.
- Digital twins use real-time and historical data to represent the past and present and simulate predicted futures.
- Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems.
- The foundational elements of the definition are captured in the first sentence: the virtual representation, the real-world entities and processes it represents, and the mechanism by which the virtual and real-world entities are synchronized

Common to all definitions:

- A virtual representation of a product/object, system, process/behavior of something in the physical/natural world
- Data is exchanged between virtual and physical systems.

So yes, it generally does smell just as sweet!

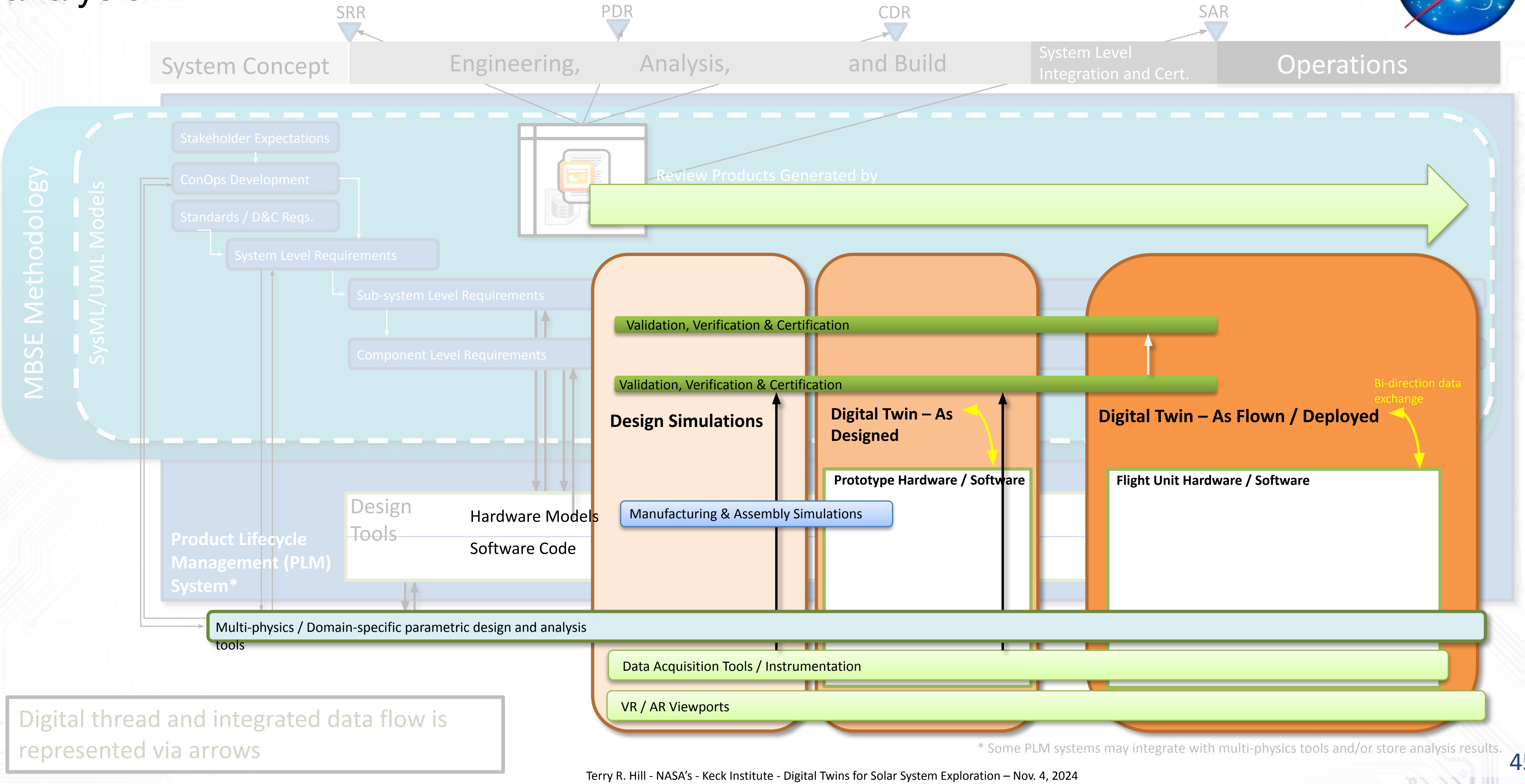
Integrated Digital Engineering Framework per Lifecycle of a Project and how Digital Twins can Evolve out of Standard Development of Engineering Models



Digital thread and integrated data flow is represented via arrows

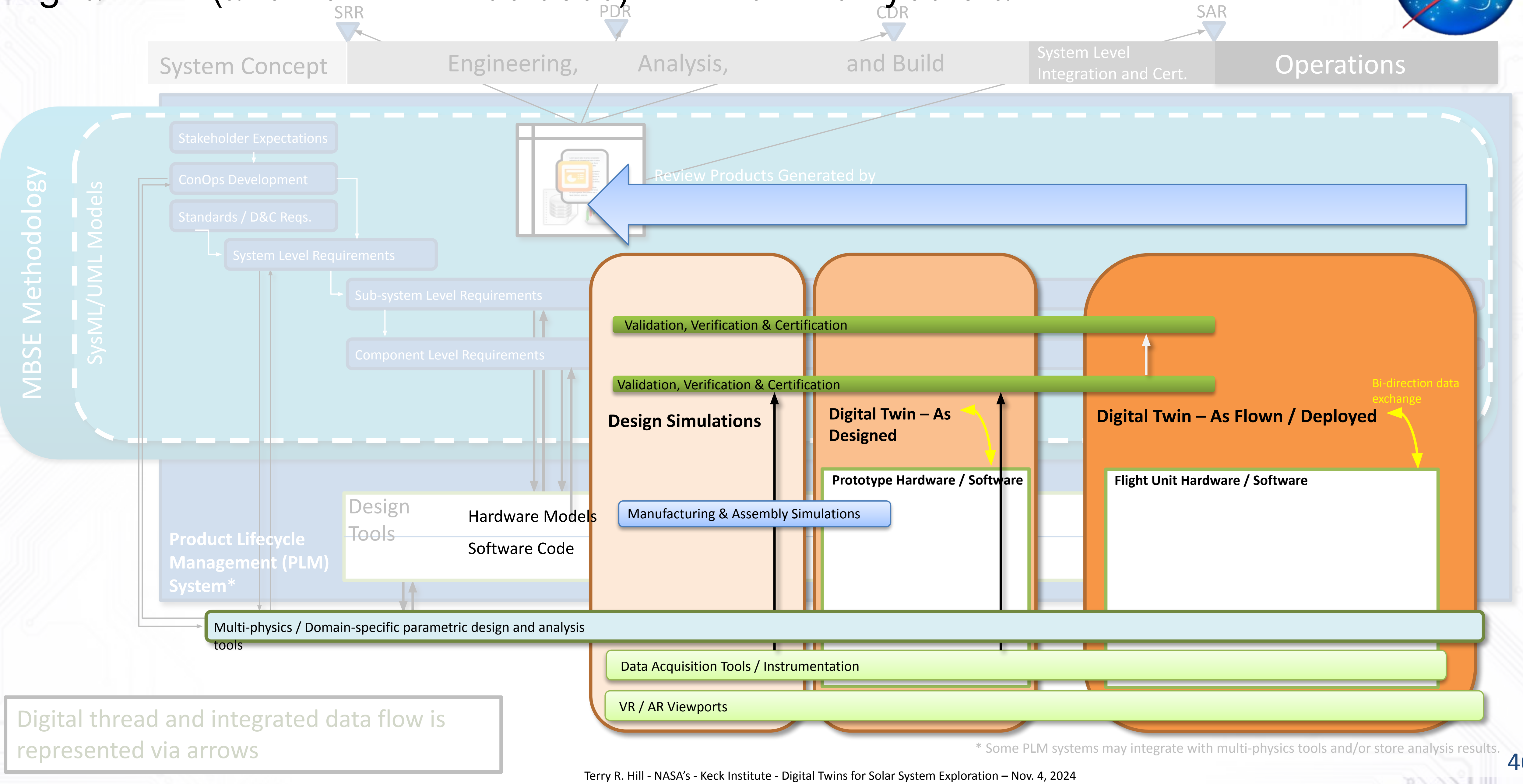
* Some PLM systems may integrate with multi-physics tools and/or store analysis results.

Digital Twins can & should be and evolution of the models used for design and analysis.



* Some PLM systems may integrate with multi-physics tools and/or store analysis results.

… But only if you build, integrate, and certify the models with the well-scoped Digital Twin (and how it will be used) in mind when you start.



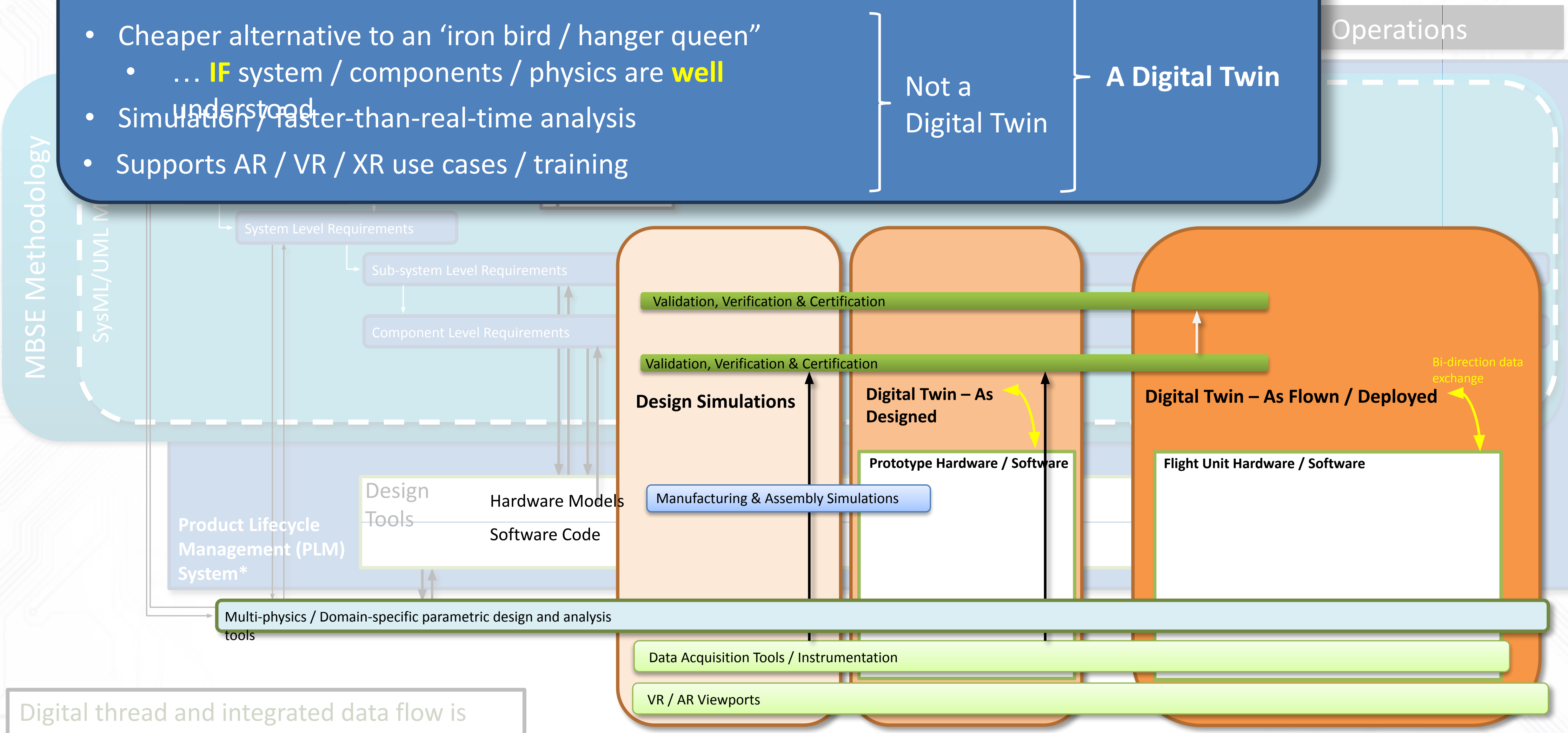
* Some PLM systems may integrate with multi-physics tools and/or store analysis results.

Benefits of Digital Twins

- Bi-directional data interaction with real-world asset
- Cheaper alternative to an ‘iron bird / hanger queen”
  - … **IF** system / components / physics are **well** understood
- Simulation / faster-than-real-time analysis
- Supports AR / VR / XR use cases / training

Not a Digital Twin

A Digital Twin

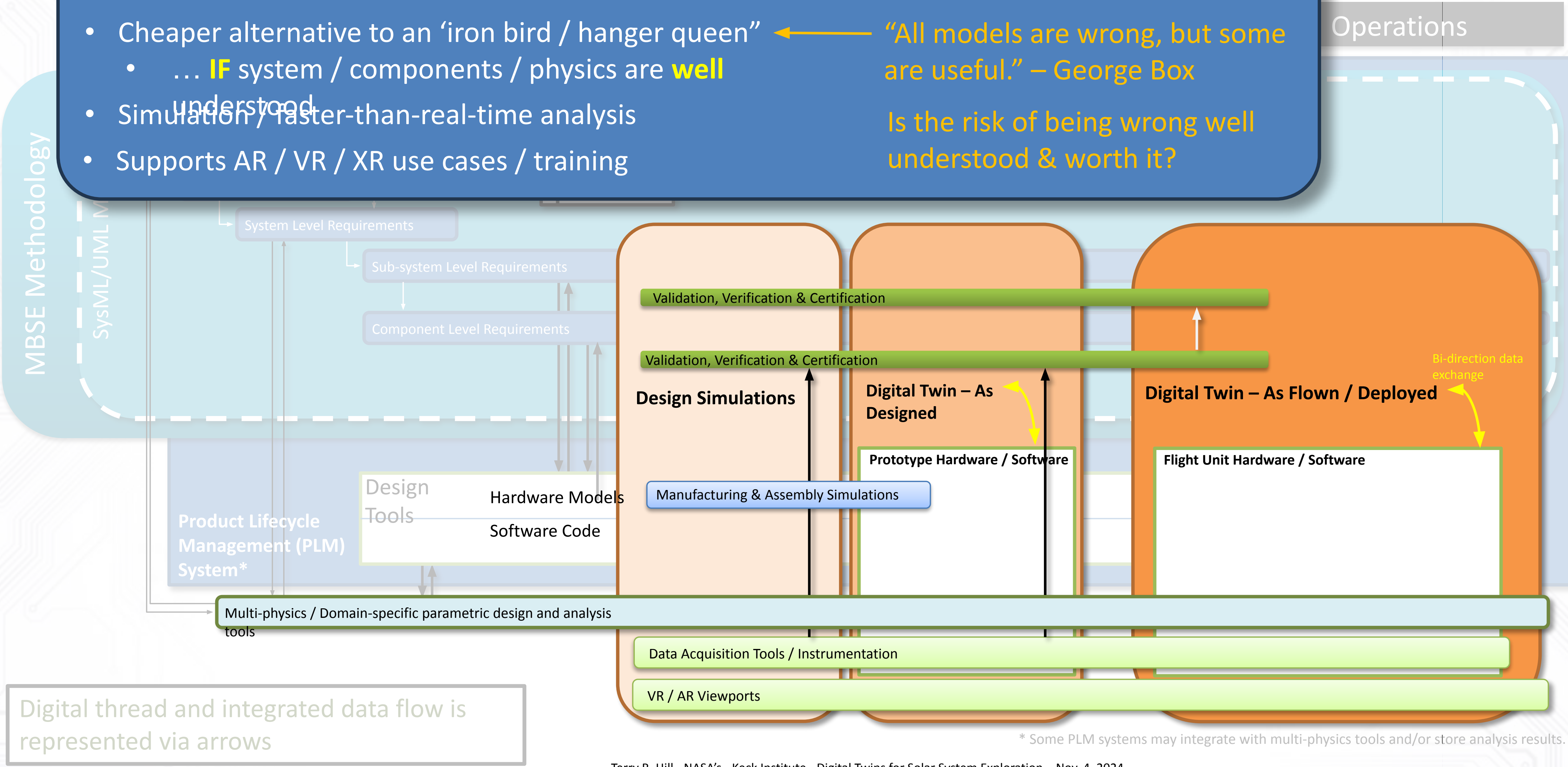


* Some PLM systems may integrate with multi-physics tools and/or store analysis results.

Things to Consider Before Creating Digital Twins

- Bi-directional data interaction with real-world asset ← What is my ROI & is it worth it?
- Cheaper alternative to an 'iron bird / hanger queen" ← "All models are wrong, but some are useful." – George Box
  - … **IF** system / components / physics are **well** understood
- Simulation / faster-than-real-time analysis
- Supports AR / VR / XR use cases / training

Is the risk of being wrong well understood & worth it?



* Some PLM systems may integrate with multi-physics tools and/or store analysis results.

Digital Twin - Use Cases

Level 1:

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

NASA Digital Twin Characteristics

Level 2:

System Type
- Human Spaceflight
- Aircraft
- Satellite
- Rover
- Facilities

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
- Manufacturing
- 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 Collaboration
- 1 Center
- 2 Centers
- 3+ Centers

* based on AIAA definition of digital twins

Explored Attribute by NASA

Digital Twin - Capabilities

- The required enabling capabilities vary significantly based on system characteristics and desired digital twin applications
- The Digital Twin Consortium has defined the following capabilities in their “Capabilities Periodic Table”

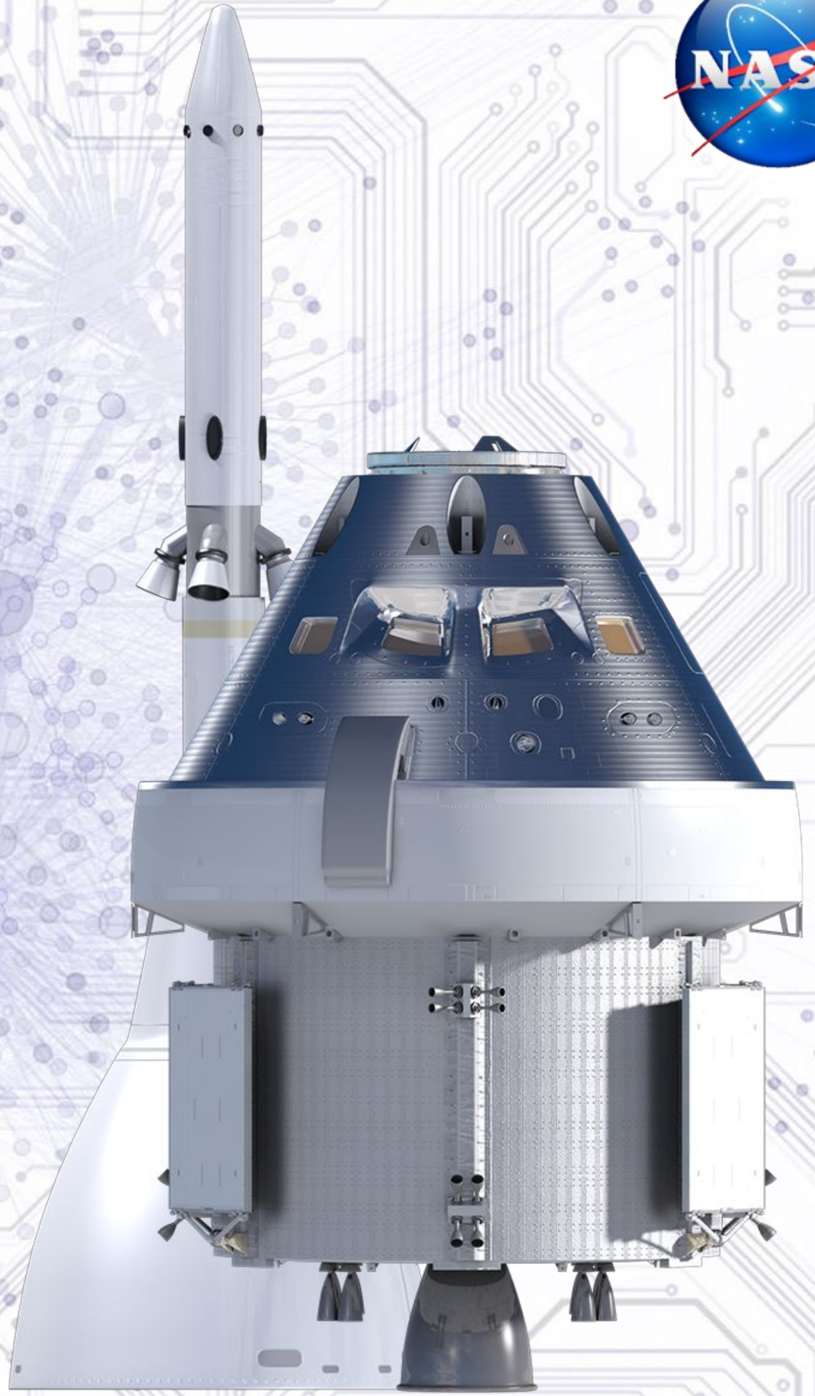
1 Data Acquisition & Ingestion	9 Synthetic Data Generation	17 Enterprise System Integration	23 Edge AI & Intelligence	29 Prediction		39 Basic Visualization	45 Dashboards
2 Data Streaming	10 Ontology Management	18 Eng. System Integration	24 Command & Control	30 Machine Learning ML		40 Advanced Visualization	46 Continuous Intelligence
3 Data Transformation	11 Digital Twin (DT) Model Repository	19 OT/IoT System Integration	25 Orchestration	31 Artificial Intelligence AI	35 Prescriptive Recommendations	41 Real-time Monitoring	47 Business Intelligence
4 Data Contextualization	12 DT Instance Repository	20 Digital Twin Integration	26 Alerts & Notifications	32 Federated Learning	36 Business Rules	42 Entity Relationship Visualization	48 BPM & Workflow
5 Batch Processing	13 Temporal Data Store	21 Collab Platform Integration	27 Reporting	33 Simulation	37 Distributed Ledger & Smart Contracts	43 Augmented Reality AR	49 Gaming Engine Visualization
6 Real-time Processing	14 Data Storage & Archive Services	22 API Services	28 Data Analysis & Analytics	34 Mathematical Analytics	38 Composition	44 Virtual Reality VR	50 3D Rendering
7 Data PubSub Push	15 Simulation Model Repository	52 Device Management	54 Event Logging	56 Data Encryption	58 Security	60 Safety	51 Gamification
8 Data Aggregation	16 AI Model Repository	53 System Monitoring	54 Data Governance	57 Device Security	59 Privacy	61 Reliability	62 Resilience

Data Services · Integration · Intelligence · UX · Management · Trustworthiness

Source: www.digitaltwinconsortium.org

Electrical Power System

ORION (ARTEMIS I) DIGITAL TWIN



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.

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

- Utilize system modeling tool MagicDraw to create a SysML model foundation for a digital twin of Orion systems that is able to provide needed insight to the operations and engineering teams. This includes:
  - Detail - and context-rich schematics
  - Web-accessibility in a COTS tool
  - System-level simulations
  - As-designed/As-tested/As-operated unit-specific data

- Development will begin 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.

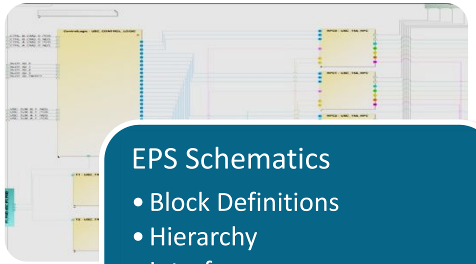
- Development could also proceed with the support of additional digital twin integration and simulation use cases.

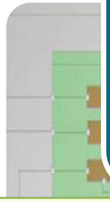
Orion Digital Twin Project 2021-2022 Activities

FY2021 | 2022

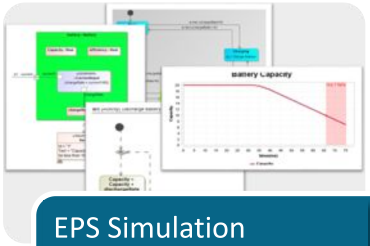
March → April → May → June → July → August → September → October → November → December → January → February → March → April → May → June → July → August → September

Development
- Prototype
- Depth Trade
- Domain Research





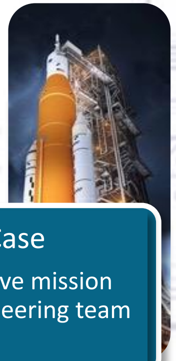
EPS Schematics
- Block Definitions
- Hierarchy
- Interfaces
- Schematic Integration
- June – Board interfaces & "Switch" details
- July – Loads
- Aug+ - Board internals



EPS Simulation
- Define Sim Scenario
- Define behavior model
- Develop GUI for live mission scenario

EPS Twin Integration
- Telemetry Interface
- Operational Data Interface
- Parameter Definition

EPS Digital Twin Validation/Evaluation
- Model-Based Review
- Live Reviews
- Automated Audits



Artemis I Test Case
- Feedback from live mission use by EPS engineering team

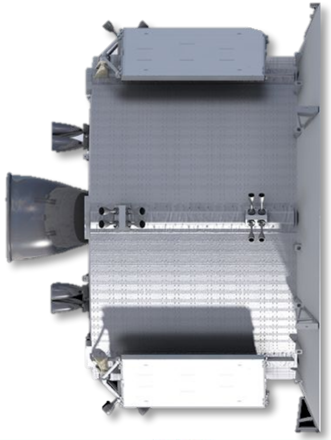
Further Subsystem Development
- Multi-Domain Simulation
- Tool Integration
- Comprehensive Digital Twin Framework

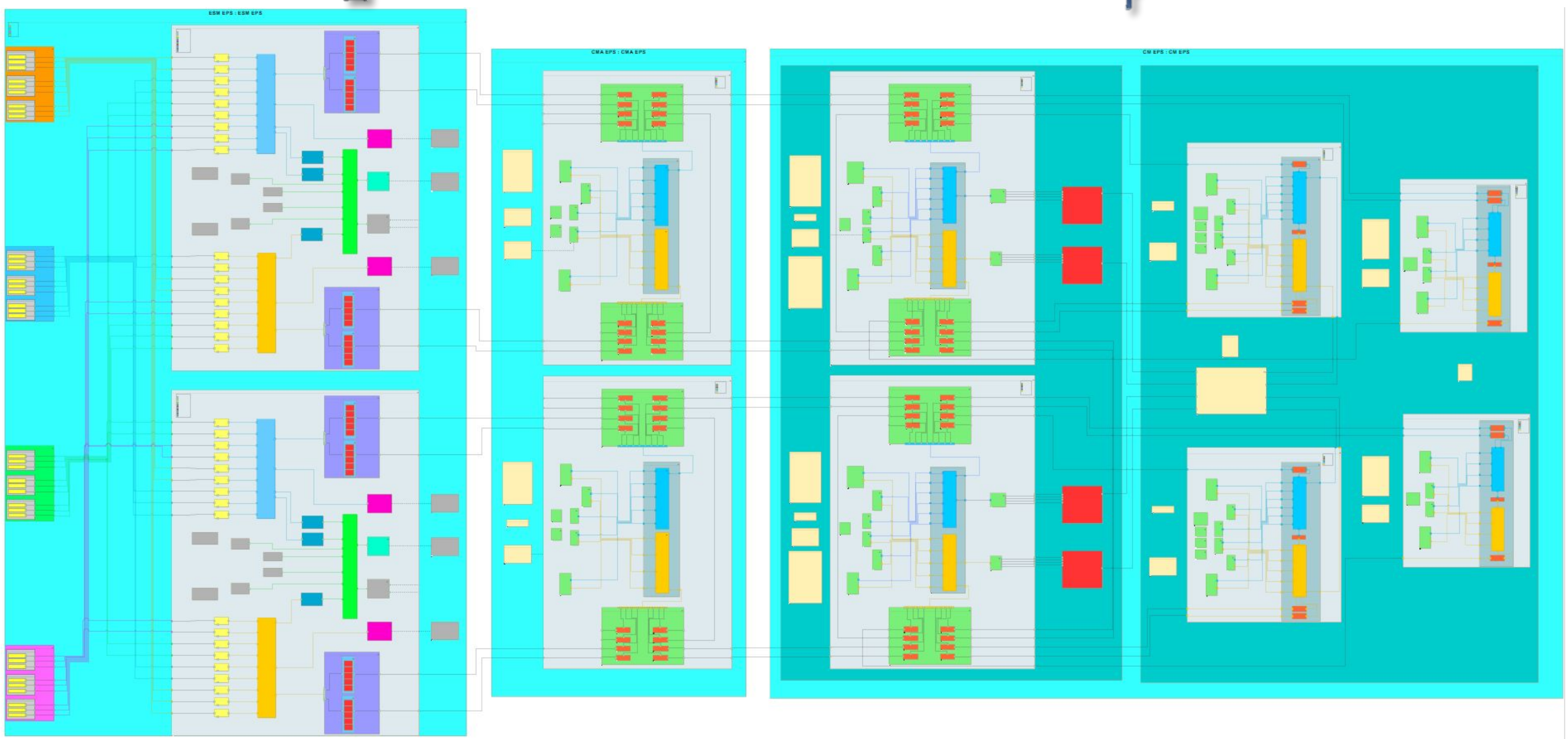
Package for Agency Wide Use
- Lessons Learned
- Sanitized Model
- Script Library
- Reusable Components

- 10 months of modeling and 8 months of validation.
- Over 9,000 components represented
- ~6000 elements of definition reused
- Over 130 hyperlinks to schematics database integrated into SysML Model
- Over 4,500 interfaces defined between components
- 2,208 ports imported ready for CD&H/Avionics/GNC subsystems
- Over 500 loads integrated into EPS architecture
- Automated syncing and validation of data and architecture to authoritative sources
- Simulation utilizing built architecture and imported component specifications

2023 INCOSE IS Best Paper in Mod/Sim Category

Orion EPS Architecture



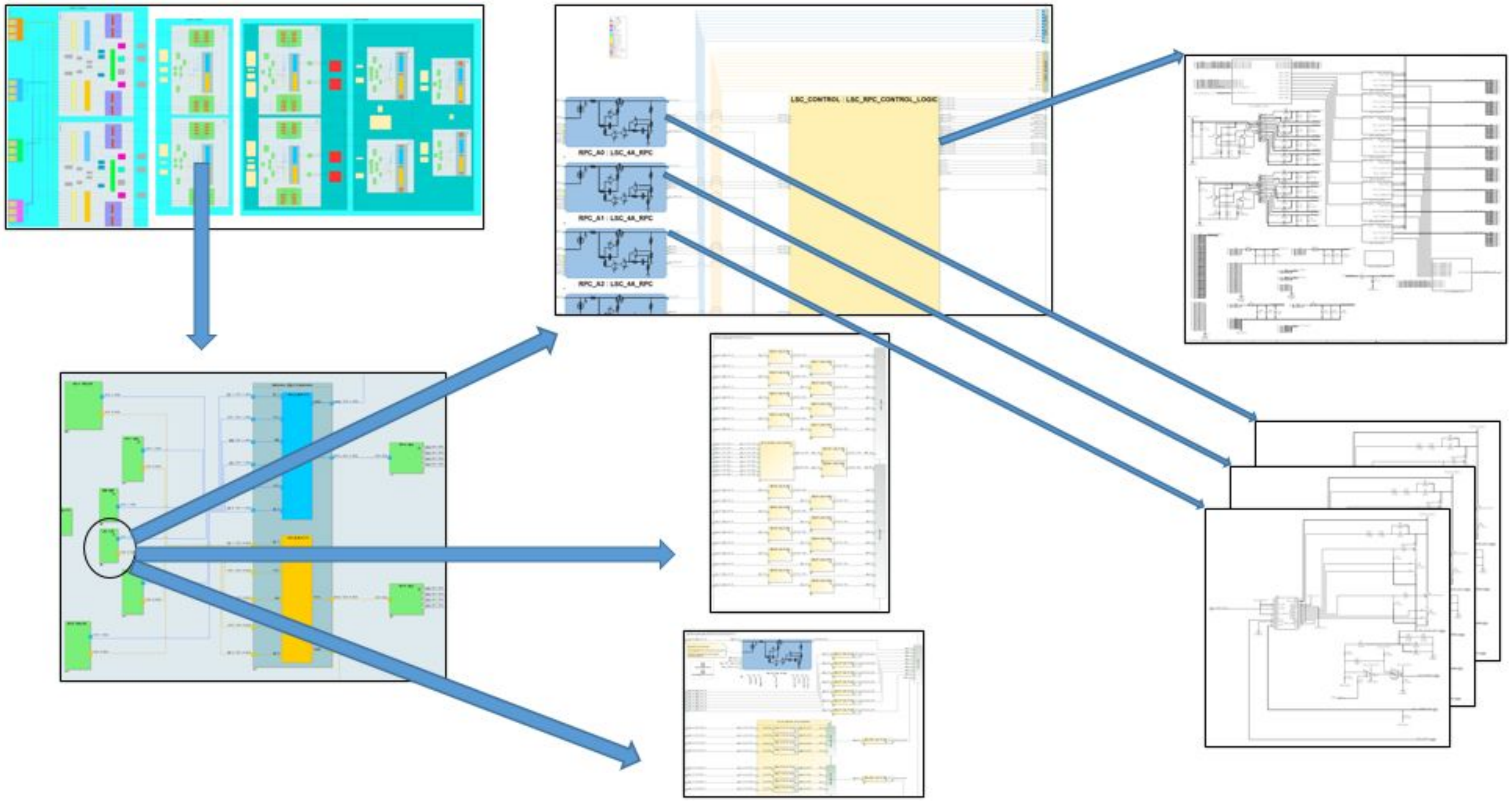


Integrated Schematics

Component Breakdown

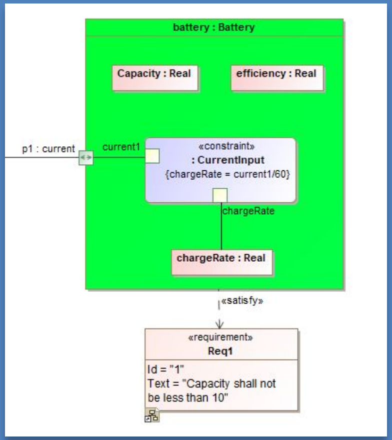
Curated Views

Hyperlinked to Manufacturing Schematic Database

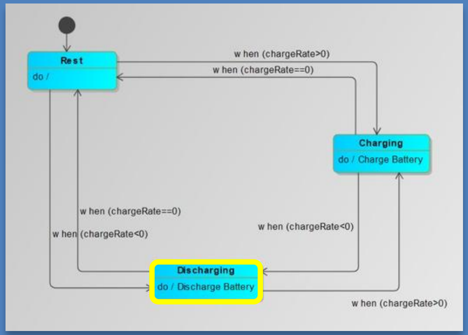


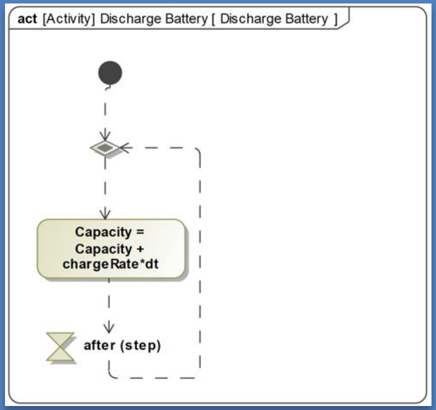
Integrated Simulation

- Interfaces
- Key Parameters
- Mathematical Relationships
- Requirements

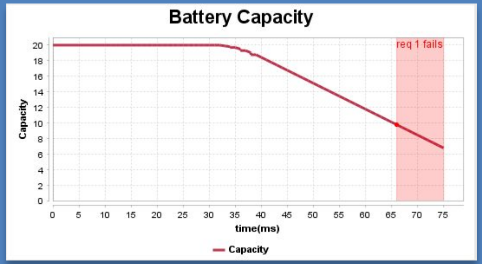


- Component Behavior

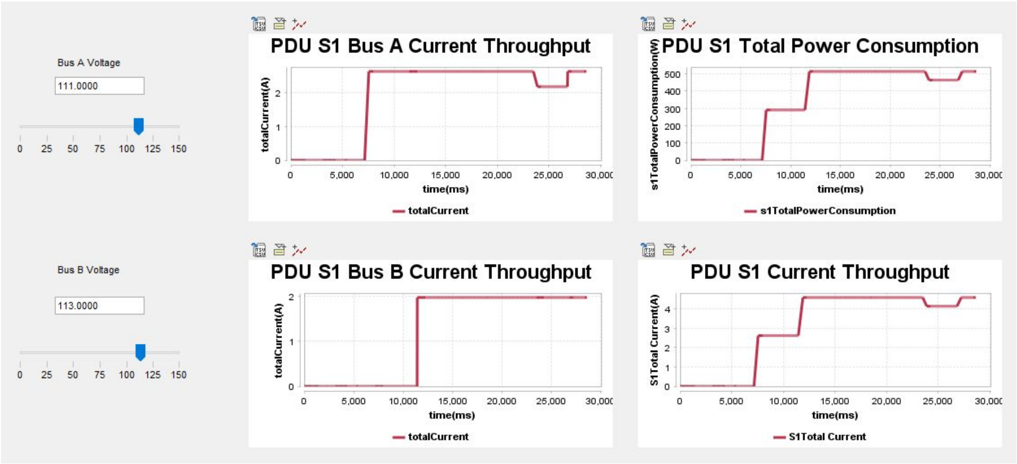




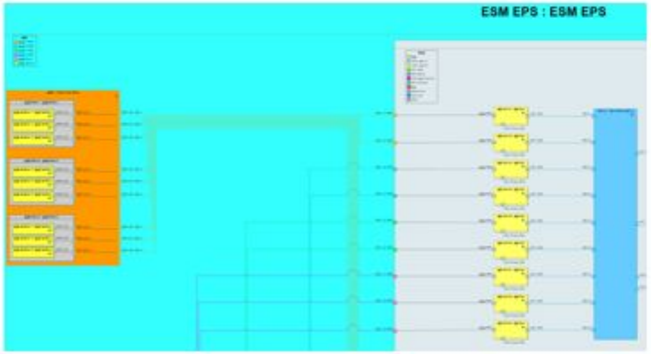
- Performance Analysis
- Verification of Requirements

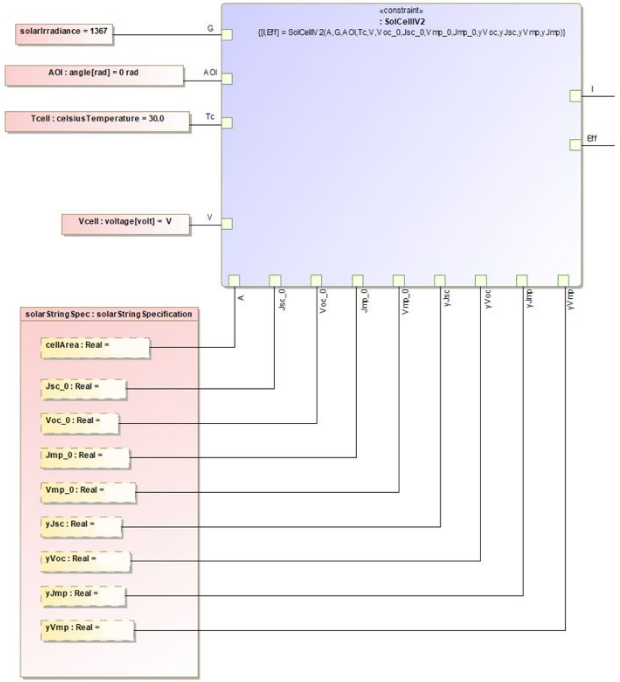


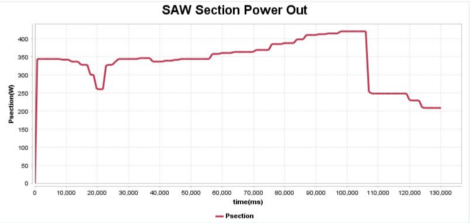
Integrated Simulation – Power Bus

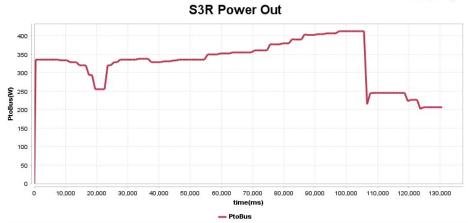


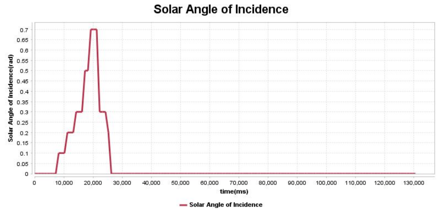
Integrated Simulation – Solar Arrays

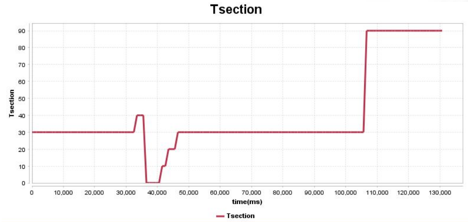


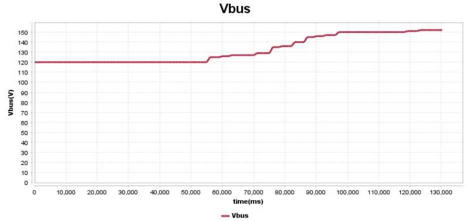












Data Driven Design / Automation

Notification Window	
[2021.08.15::22:12:53]	The card: CLSC003 on port: LSC1_4A_RPC_OUT_B3 is missing the load: Crew Console Payload
[2021.08.15::22:12:53]	The card: CLSC004 at port: LSC1_4A_RPC_OUT_A0 has a load that is missing a REFDES in the model
[2021.08.15::22:12:53]	The card: SLSC001 at port: LSC1_4A_RPC_OUT_B4 has a load that is missing a REFDES in the model
[2021.08.15::22:12:53]	The card: SLSC001 at port: LSC1_4A_RPC_OUT_A3 has a load that is missing a REFDES in the model
[2021.08.15::22:12:53]	The card: SLSC001 at port: LSC1_4A_RPC_OUT_A4 has a load that is missing a REFDES in the model
[2021.08.15::22:12:53]	The card: SLSC002 at port: LSC1_4A_RPC_OUT_A4 has a load that is missing a REFDES in the model
[2021.08.15::22:12:53]	The card: SLSC002 at port: LSC1_4A_RPC_OUT_B4 has a load that is missing a REFDES in the model
[2021.08.15::22:12:53]	342 loads have been verified

MagicDraw API Automation

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

Document Revision Traceability to Model Elements

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

Legend
↗ Implied Relation

02_Schematics		Printed Wiring Assembly And Schematic - L	Printed Wiring Assembly And Schematic, Un	Schematic Diagram - Power Data Unit Conti	Schematic Diagram, Backplane, C1/C2	Schematic Diagram, Backplane, C3/C4	Schematic Diagram, Backplane, C5/C6	Schematic Diagram, Backplane, S1/S2	Schematic Diagram, Battery Charge Control	Schematic Diagram, Battery Charge Control	Schematic Diagram, Crew Module Propulsio	Schematic Diagram, Heater Control	Schematic Diagram, Internal Power Supply	Schematic Diagram, Pyro Event Controller	Schematic Diagram, Solenoid Drive Output
Cur Lim SW	3				↗				↗	↗					
CURRENT_SOURCE_OUT	4				↗		↗	↗				↗			
DC_DC_Power_Supply	3				↗	↗		↗							
DGND_BUS	1				↗										
DS_1A_RPC	2					↗									↗
DS_1A_Switch	5	↗			↗	↗	↗	↗							
DS_1A_Switches	5	↗			↗	↗	↗	↗							
EDE	3				↗	↗		↗							
EMI Filter and Input Cur	3					↗		↗						↗	
EMI_FILTER	5				↗	↗	↗	↗					↗		
Feeder Switch	2					↗	↗								
Gate_Drive_Inhibit	5				↗	↗	↗	↗					↗		
HCC	4				↗		↗	↗				↗			
HCC_AGND	4				↗		↗	↗				↗			

Name	Drawing Number	Date	Revision	Cage Code
CM Electrical Checkout Diagram	948CN2000012	24/11/20	-	04236
Schematic Diagram, Backplane, S1/S2	948BA1711111	03/10/14	-	04236
Schematic Diagram, Battery Charge Control, Part A	948CA1712311	01/11/16	D	04236
Schematic Diagram, Battery Charge Control, Part B	948CA1712511	01/11/16	B	04236
Schematic Diagram, Backplane, C1/C2	948CA1715111	09/19/14	-	04236
Schematic Diagram, Heater Control	948CA1715311	06/24/14	-	04236
Schematic Diagram, Internal Power Supply	948CA1715511	01/22/15	-	04236
Schematic Diagram, Backplane, C3/C4	948CA1716111	01/12/14	A	04236
Schematic Diagram, Pyro Event Controller	948CA1716211	11/25/14	-	04236
Schematic Diagram, Solenoid Drive Output	948CA1716311	02/25/15	-	04236
Schematic Diagram, Crew Module Propulsion Driver	948CA1716411	01/11/14	A	04236
Schematic Diagram, Backplane, C5/C6	948CA1717111	01/12/14	A	04236
Printed Wiring Assembly And Schematic, Umbilical Switch Car	1722585	06/17/16	C	47PP5
Printed Wiring Assembly And Schematic - Load Swith Card	1722595	11/25/15	A	47PP5
Schematic Diagram - Power Data Unit Controller	8275781	10/23/14	B	61962
ODB Volume II EEL		12/11/21	J	

Source of Truth

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.

Status and Updates

- Orion Artemis I EPS Model is functional and validated
- Artemis I evaluation by EPS system management team

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

- Lessons Learned Captured
  - 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

Another DT Example: Inter-Agency Working Group for Digital Twins for Predicting System Failure

Kicked off in Aug. ‘24

- A Failure Occurred in a System
  - Human Failure
    - Insufficient Training
    - Insufficient Capabilities
    - Insufficient Working conditions
  - Process Failure
    - Process Escape (due to Human)
    - Process Escape (unanticipated operational conditions - Insufficient design)
    - Insufficient Process efficacy monitoring
  - Technical Failure
    - Power
    - Hardware
      - Insufficient Maintenance
        - Insufficient Requirements
        - Process failure
        - Insufficient Funding
      - Normal Wear
        - Insufficient definition of End of Life
      - Insufficient Design
    - Software
      - Insufficient Testing
      - Insufficient Design
    - Network
      - Voice
      - Data

Utilizes a root-cause failure identification approach to determining what the digital twin needs to do and what data is required

Which of these contributors (or others) to a system failure do you want to model with a digital twin?

’Cause you can’t model the universe with a DT.

Digital Twin – Fingerprint

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

System Characteristics

- Class & Criticality
- Scale
- Domain

Capabilities

- Data Services
- Integration
- Intelligence
- User Experience

Twininess

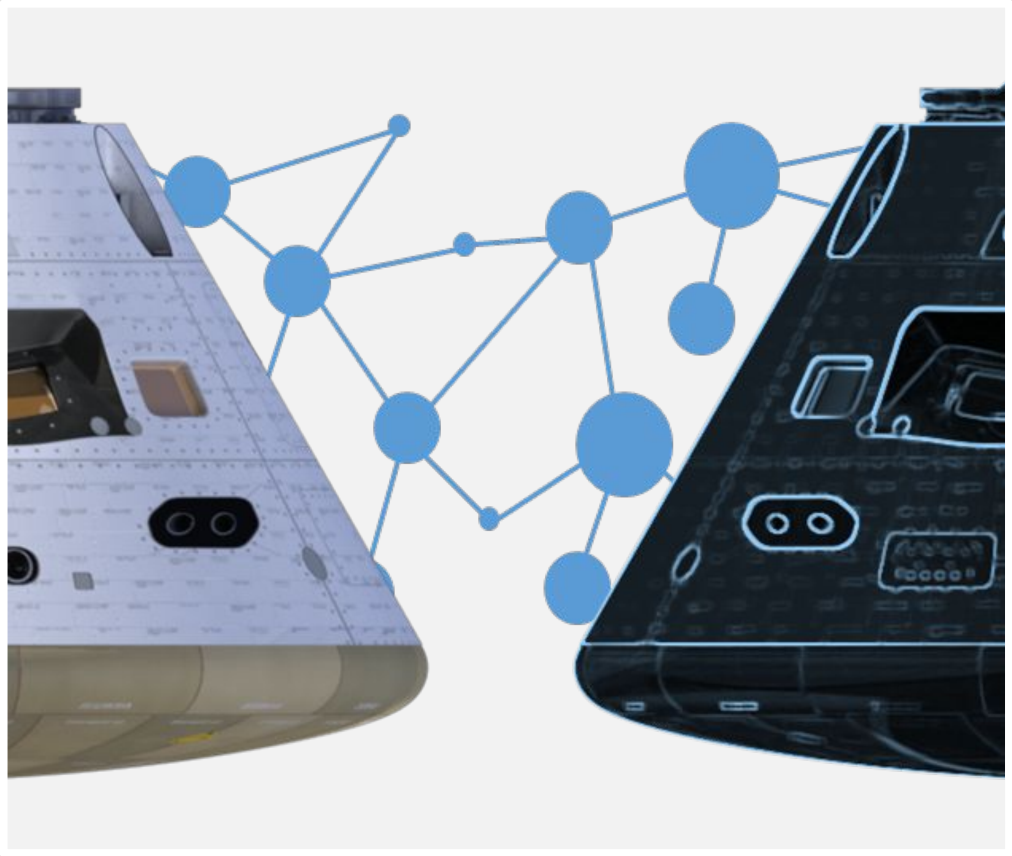
The extent, by which both scope and degree, a system model is a digital twin.

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



Lessons learned, bottlenecks, what not to Digital Twin

Reference Mission: Europa Clipper

Lessons Learned come from *SE Lessons Learned: Europa Clipper*, Ann Devereaux: JPL Division Manager for SEI&T, Richard Kornfeld: JPL Section Manager for Flight Systems, August 2020

Note: This project was pathfinding with the use of MBSE, so being one of the first always means there are lessons to be learned by others. Nothing but respect for this team!

While the Lessons Learned do not pertain specifically to digital twins, they are very relevant given that digital twins are based upon modeling and is a relatively new technology approach much like SysML modeling was for this team.

Europa Clipper: Lessons Learned

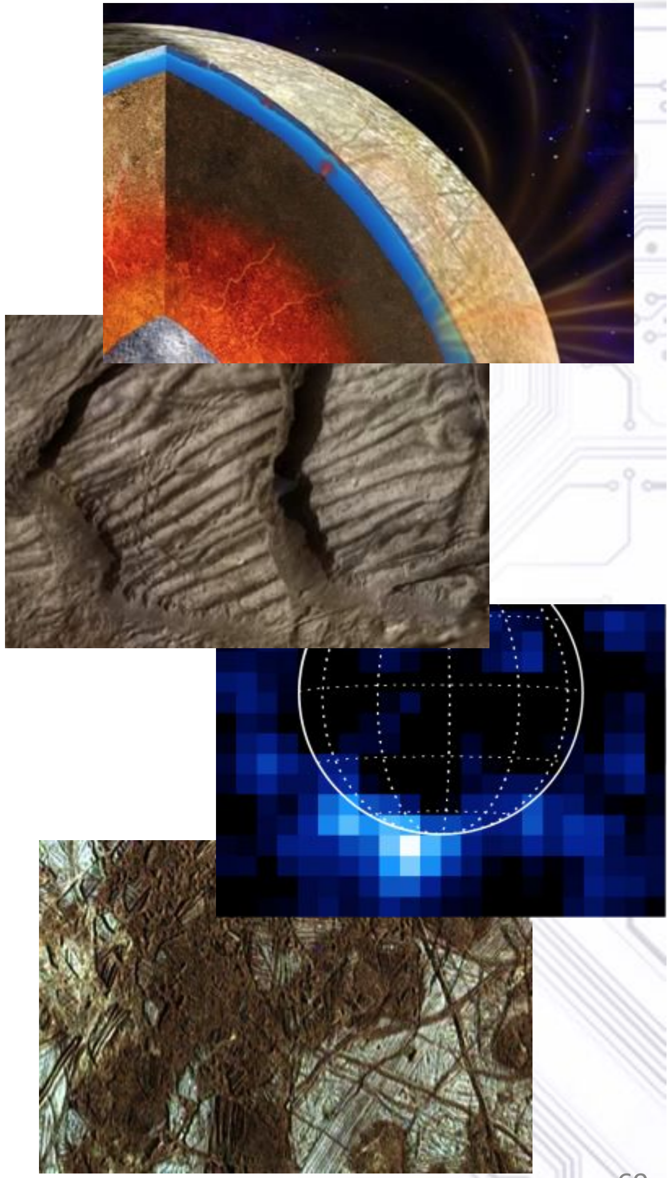
Architectural Framework team attempted to apply same extreme level of rigor to all mission elements, and failed to scale efforts commensurate with relative return on investment for various areas.

The quest to prove "completeness" in architecting, etc. to be achieved via the "mechanization" of the SE function, might not necessarily be justified in all cases; instead, it should be applied judiciously, i.e. where the return on investment warrants it.

Perfect is the enemy of good…

"Striving to better, oft we mar what's well" – Shakespeare 1606

"Give them the third best to go on with; the second best comes too late, the best never comes." - Robert Watson-Watt (1892-1973)



Artificial Intelligence and Digital Twins

How should we use Artificial Intelligence in the development of, or use with, digital twins?

Artificial Intelligence and Digital Twins

Suggestions:

Renamed as Augmented Intelligence?

Use it for activities which eat up a lot of human labor time with minimal value?

Use it to help keep track and status of our processes and systems, functionality, and health?

Use it to analyze data / information which is ill suited for humans in a timely manner?

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NASA DIGITAL TRANSFORMATION

Questions?