Integrating Digital Engineering Needs into Physics-Based Modeling and Simulation for Aircraft Power and Thermal Systems

Paper 343

Daniel R. Herber (presenting author)
Dominic Dierker
Brian Raczkowski
Nathaniel J. Butt
Soumya S. Patnaik

daniel.herber@colostate.edu
Colorado State University – Department of Systems Engineering

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Outline

1. Introduction
2. Background
3. Current Digital Engineering Strategy and Digital Ecosystem
4. Self-Assessment Based on INCOSE MBCM Capabilities
5. Conclusions and Future Work

①

Introduction

Introduction

- Digital engineering (DE), digital transformation (DT), and model-based systems engineering (MBSE) are all strategic initiatives that various organizations are enacting or considering to meet the challenges of the modern world
- There are various types of decisions, each with numerous alternatives, that may achieve the desired outcomes of these principles
- In 2018, the DoD Digital Engineering Strategy[1] outlined five broad strategic goals for their DE initiative
- While the flexibility allows for many new opportunities to meet the strategic goals, there are still many challenges to effectively realizing the DE vision

[1] ODASD(SE) 2018; Possehl et al. 2022

→ Physics-Based Modeling and Simulation (M&S) Team Focus

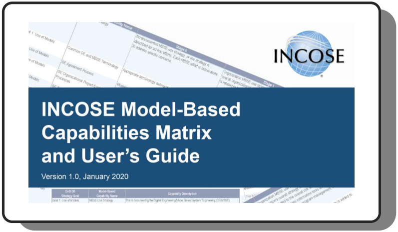
- Here, focus is on a team with existing prioritization of **physics-based modeling and simulation (M&S)**, and part of a larger organization (and then enterprise)
  - Focuses on developing and using computational models grounded in the fundamental laws of physics and experimental data to simulate real-world phenomena
  - Supports prediction, testing, analysis, and other activities while reducing the need for physical prototypes or experiments
- We will show some key insights into the M&S team's ongoing DE/DT/MBSE effort
  - Includes **current DE strategy and digital ecosystem**, with templates for other similar M&S teams to consider
  - Self-assessments using the **INCOSE Model-Based Capabilities Matrix (MBCM)** will highlight and justify various aspects of the ongoing DT effort

→ Literature Review and Some Important Observations

- Some observations about the state-of-the-art:
  - Many DT efforts provide important insights at the enterprise level (potentially 1000s of people), but challenges exist when applying them to smaller teams (10s of people) where resources, expertise, and goals might be different[1]
  - Much of the related research focuses on technical solutions and processes to achieve various goals like tool integration, interoperability, or traceability[2] or acquisition[3]
  - Often overlooked is the social context[4] and balance of the delivery of value in the context of existing capabilities, processes, and people — “means of communication across a diverse set of stakeholders”
- Further insights were found in these references[5]

[1] Pierce et al. 2024; McDermott et al. 2020 [2] Hällqvist et al. 2022; Ma et al. 2022; Rashi, Anwar, and Khan 2015; Santiago et al. 2012 [3] Cortes et al. 2021 [4] Morales et al. 2019 [5] Cederbladh, Cicchetti, and Jongeling 2024; Snyder et al. 2024; ISO/IEC/IEEE 2023

→ INCOSE Model-Based Capabilities Matrix (MBCM)



- The MBCM[1] is *"a tool to help organizations that have already decided to implement digital engineering or Model-Based capabilities assess, and then plan the development of these capabilities in a comprehensive and coherent manner"*
  - 42 model-based capabilities (MBCs) are defined
  - There are five increasing stages of an MBC (0–4) with definitions
- Limited examples of this tailoring and assessment of the MBCM exist in the literature but currently include the references below[2]

[1] Hale and Hoheb 2020 [2] Pierce et al. 2024; Nolder 2023

→ MBCM Modeling Tool Access Example

Exhibit 6. DoD DE Strategy Goal Example for Strategic Vision

DoD DE Strategy Goal	Model-Based Capability Name	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4
Goal 4. Establish Environments	Modeling Tool Access	Model access is based on desktop access.	Access to models are based on IT login.	Access to models are based on role-based permissions.	Model access permissions are shared within a project/program.	Model access permissions are shared within an enterprise.
Goal 4. Establish	Model Based Tool	None or Unmanaged.	Tool licenses and	Tool licenses and	Center-wide license	License count

[1] From page 21 of Hale and Hoheb 2020

②

Background

→ Organizational Context (1)

- Greater awareness of the organizational context provides a means for reasoning through the decisions that need to be made and were made
- We make an attempt here to generalize these characteristics for the broader applicability of this work and meaningful insights
- M&S team considered here focuses on physics-based M&S team capabilities for power and thermal systems for aircraft in a mostly defense-oriented context

Organizational Context (2)

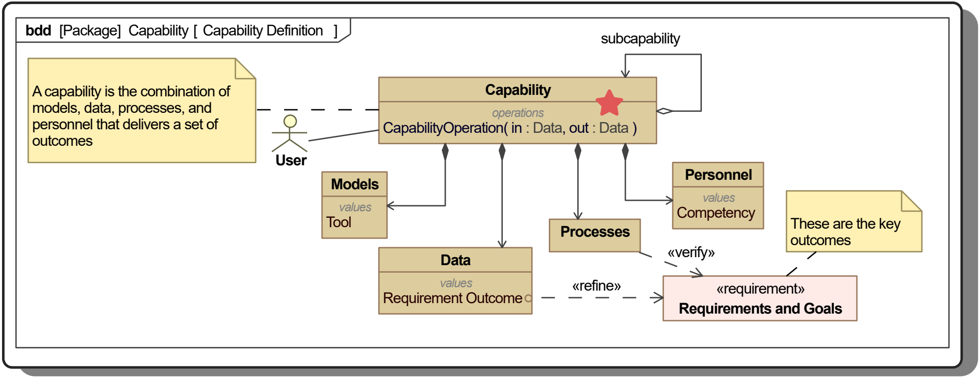
- An established M&S team on the cutting edge of a **specialty engineering discipline** (e.g., power/thermal systems for aircraft) but **often interfaces with other general and specialty disciplines** (e.g., holistic aircraft design or structures)
- Activities vary from delivering on specific requirement sets (e.g., specific program and mission needs) to exploring new technologies and potential solutions with fewer restrictions (e.g., concept exploration and low TRL solutions)
- A significant portion of the existing and future development efforts are simulation and related capabilities in **existing tool development environment (e.g., MATLAB/Simulink)** resulting from the need for high-fidelity/detailed models for hardware validation and digital twin capabilities
- M&S team is supported in various ways by **internal and external roles** (e.g., other teams in the enterprise, external governmental organizations, industry, and universities) to meet diverse stakeholders' outcomes of the R&D
- Diversity of **information limitation scenarios** where models, data, and outcomes are selectively shared based on the sensitivity of the information (e.g., proprietary in nature or defense classification)

Capability Focus

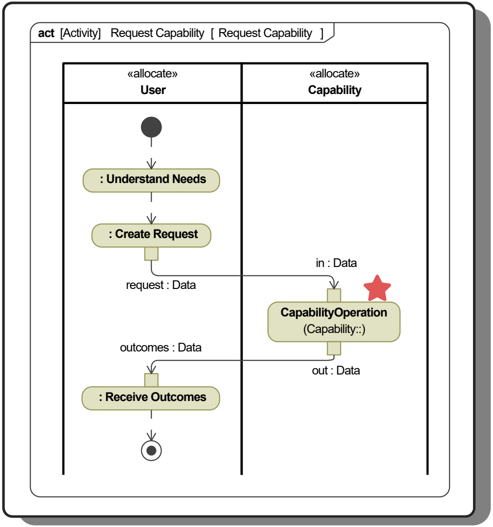
- A central concept of this paper is centered around the M&S team's capabilities
- A **capability** is defined as a combination of models, data, processes, and personnel (including various competencies[1]) that delivers a set of outcomes
  - A capability is something that an organization owns, develops, and maintains within a digital ecosystem

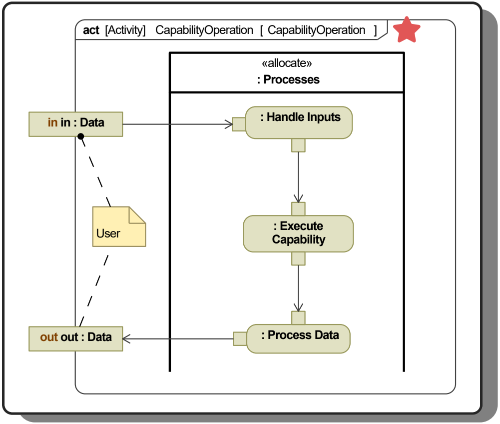
[1] Amenabar et al. 2025

→ Capability Definition

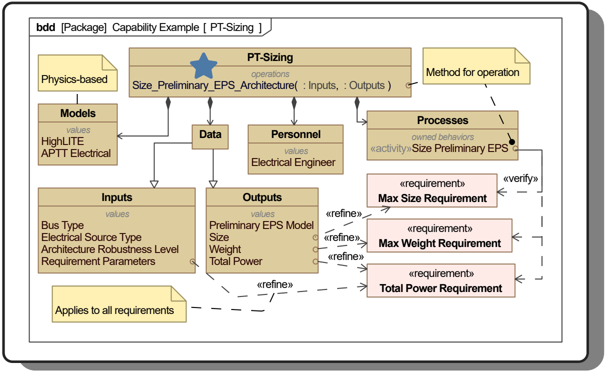


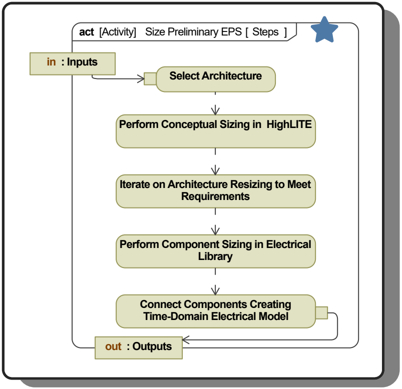
→ Illustrative Activities for Requesting and Execution of a Capability





→ Example Capability for Preliminary Electrical Power System (EPS) Sizing





[1] *PT-Sizing* is discussed more on Slide 25 and 26

→ Key Stakeholder Considerations

- We recognize the key stakeholder considerations (SCs) that summarize the current digital transformation effort for the M&S team[1]

[SC1] Capabilities are improved from reusability and agility perspectives **[objective]**

[SC2] Capabilities are easier to communicate and share with internal and external stakeholders **[objective]**

[SC3] Capabilities perform effectively within current organizational competencies, tools, and models ***[constraint]***

[SC4] The (changes to) digital engineering strategy better standardizes the organization's processes, models, data, and terminology **[objective]**

[SC5] The digital engineering strategy works within the current digital engineering environment and plans for the immediate future environment ***[constraint]***

[1] This framing has some similarities to Amorim, Vogelsang, and Canedo 2022

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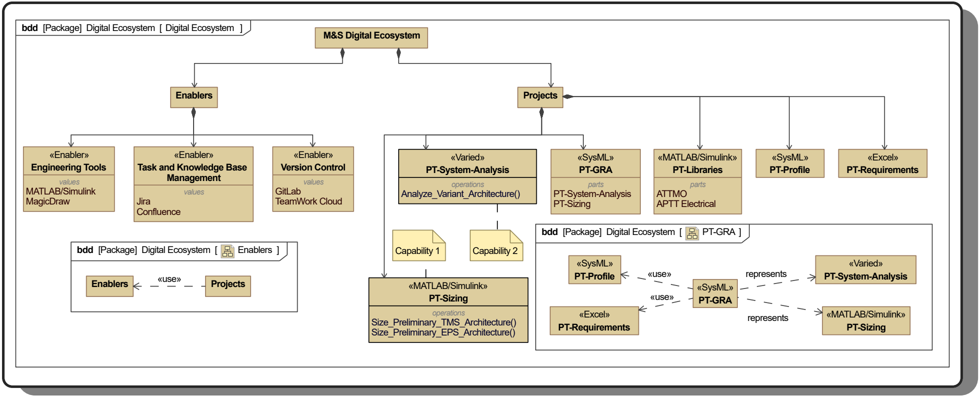
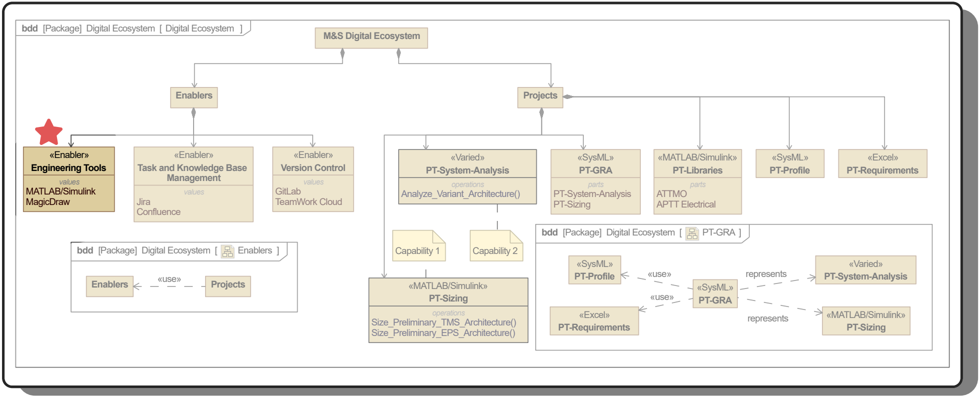
Current Digital Engineering Strategy and Digital Ecosystem

Digital Ecosystem Partial Overview (1)



→ Digital Ecosystem Partial Overview (2)

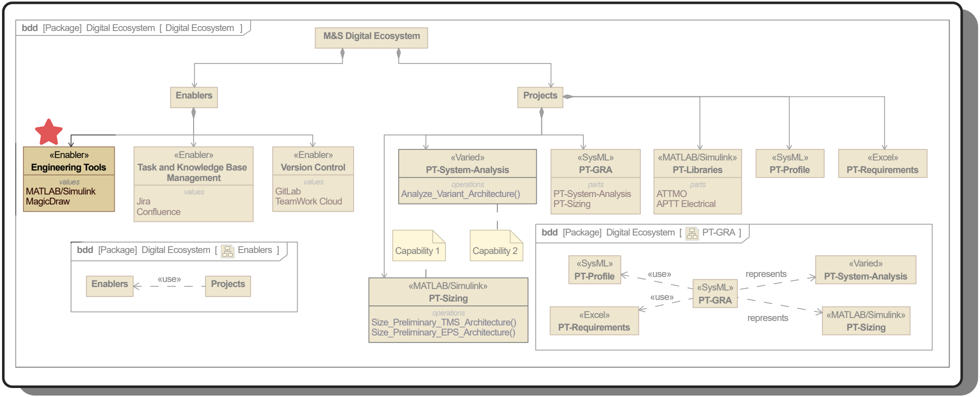
- *Engineering tools* — Key tool before and continuing is MATLAB/Simulink[1] and was already generally available to the broader M&S team; what was not generally available was SysML-based tools (SC3 and SC5)



[1] The MathWorks 2025a; The MathWorks 2025b

→ Digital Ecosystem Partial Overview (3)

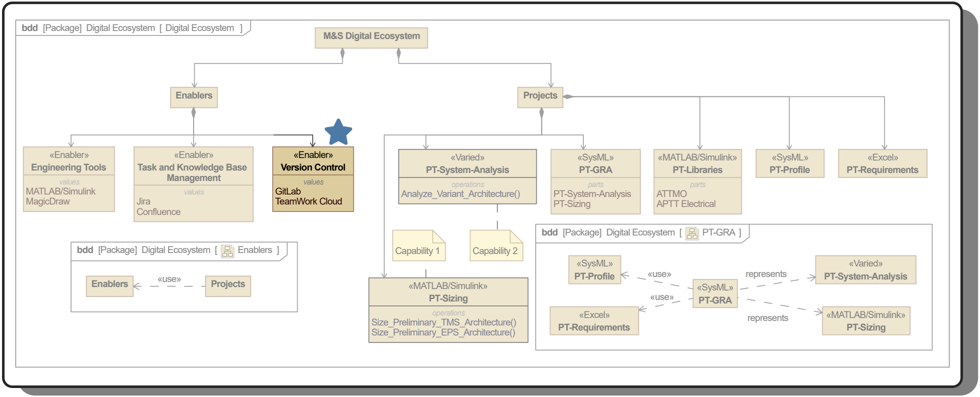
- *Engineering tools* — Transition from single-user to a broader floating license structure has been completed for MagicDraw[1,2] and Magic Model Analyst[3,4]



[1] Cameo Systems Modeler/Magic Systems of Systems Architect [2] Dassault Systèmes 2025b [3] Cameo Simulation Toolkit [4] Dassault Systèmes 2025a

→ Digital Ecosystem Partial Overview (4)

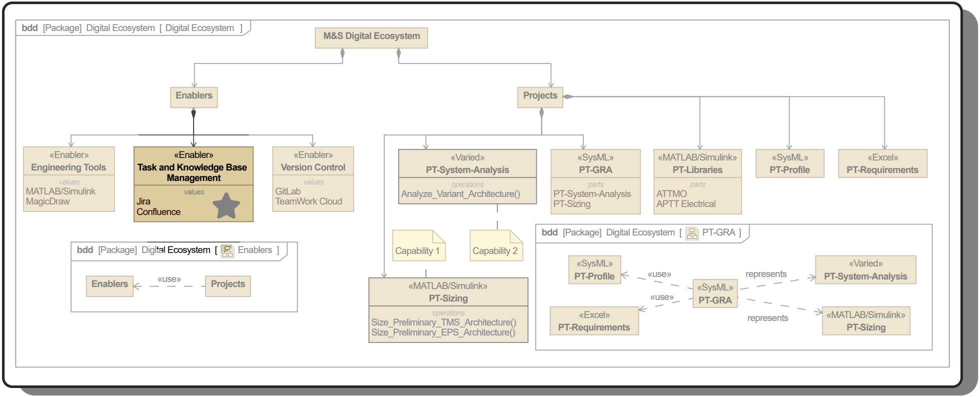
- *Version control* — For key projects, version control within GitLab[1] was adopted; Teamwork Cloud[2] for SysML models (SC5)



[1] GitLab 2025 [2] Dassault Systèmes 2025c

→ Digital Ecosystem Partial Overview (5)

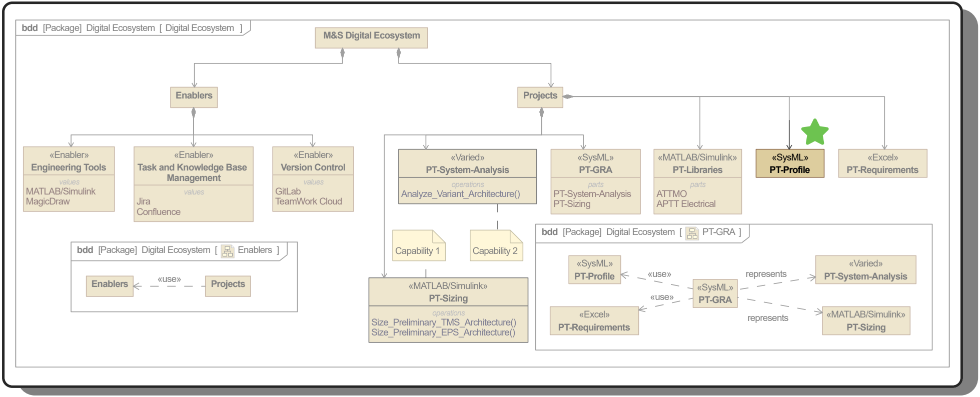
- *Task and knowledge base management* — Jira[1] and Confluence[2] (SC5)



[1] Atlassian 2025b [2] Atlassian 2025a

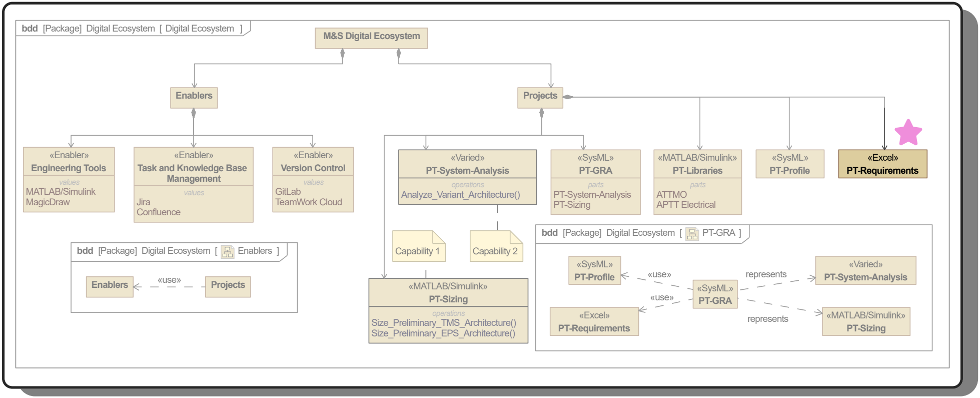
→ Digital Ecosystem Partial Overview (6)

- *PT-Profile* — SysML model that captures organizational-specific concepts and reusable elements with things like stereotypes, glossary, etc. (SC4)



→ Digital Ecosystem Partial Overview (7)

- *PT-Requirements* — Excel-based such that the requirements are reusable and tailorable in both SysML models and simulation environment (SC1 and SC2)



→ *PT-Libraries*

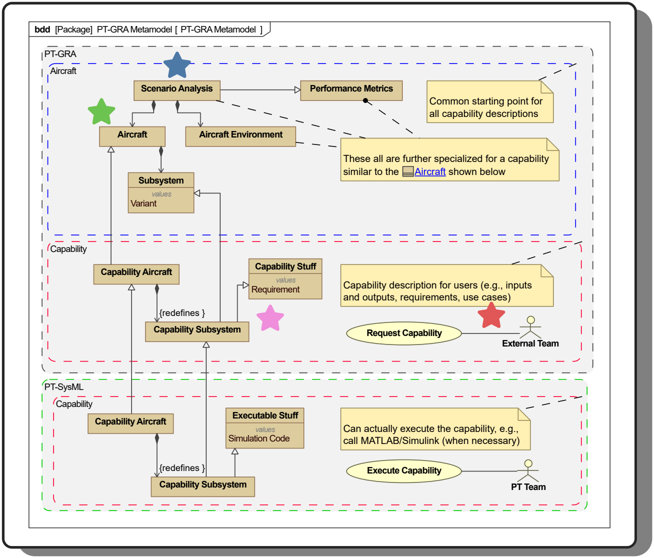
- Mostly existing infrastructure in MATLAB/Simulink for the M&S team that is not considered a full capability but rather *capability-enabling* through their usage in a capability that designs a specific aircraft
- This list includes Simulink-centric libraries:
  - AFRL (Air Force Research Laboratory) Transient Thermal Modeling and Optimization (ATTMO) toolbox[1] for thermal components
  - Aircraft Power and Thermal Toolkit (APTT) Electrical Library for electrical power system component models[2]
- There are many other existing libraries with varying dependencies on each other

[1] McCarthy, McCarthy, Hasan, et al. 2019; McCarthy, Niedbalski, et al. 2016; McCarthy, McCarthy, Wu, et al. 2014; Kania et al. 2012 [2] Boyd et al. 2019

→ Description of *PT-GRA*

- Main use here was for this **government reference architecture (GRA)** to guide and constrain potential aircraft power and thermal design capabilities
  - This is a new component of the DE strategy
- A partial metamodel of the content and organization are shown on Slide 24
- Of primary value was meeting SC2 with non-executable, collaboration-friendly forms of the various capabilities
- A primary use case — ★ External Team to Request Capability from M&S team
- To enable consistent definition and understanding for both internal and external users (SC4), the top-level PT-Aircraft package was developed that contained the key concepts and structure of a ★ Scenario Analysis
  - Then contains an ★ Aircraft, Aircraft Environment, and Performance Metrics
  - These blocks are intended for specialization at the capability level through ★ SysML generalization and redefinition (e.g., with requirements that are assessed for specific capabilities)
- Now, new capability models can be added as needed

→ *PT-GRA* Metamodel for the M&S Team's Capabilities



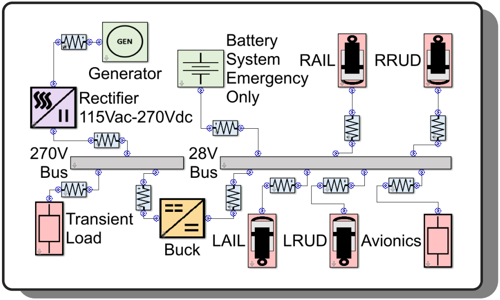
→ Capability 1 — *PT-Sizing*

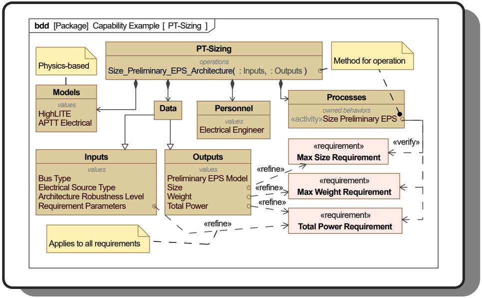
- The core parts of this capability existed *before* the DT effort
- Here, the DE strategy focuses not on directly integrating or refactoring the models, tools, data, etc., but rather on maintaining a collection of diagrams and model elements within *PT-GRA* (SC2)
- Two specific operations modeled for TMS and EPS sizing, respectively (see Slide 15 for them in the DE and Slide 13 for EPS sizing operation)
- These operations use power and thermal SWaP sizing tools:
  - High-Level Integration Sizing Tool for Electrical Architectures[1] (HighLITE)
  - Unified System of Systems[2] (UniSyS)

[1] Raczkowski et al. 2022; Patnaik et al. 2024 [2] Manion, Malatesta, and Jain 2022; Glebocki et al. 2022; Glebocki 2022; Bolander et al. 2024

→ HighLITE onto *PT-Sizing* Operation

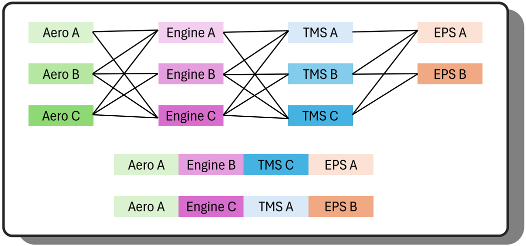
- HighLITE enables rapid EPS architecture SWaP calculations using relevant commercial-off-the-shelf (COTS) databases and advanced design tools

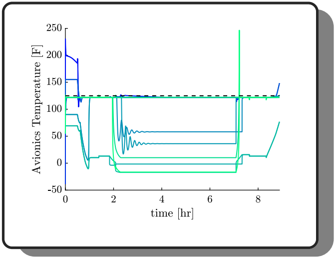




HighLITE Simulink Models ⟷ *PT-GRA* Operation SysML Model

→ Capability 2 — *PT-System-Analysis*





- Architecture-centric capability[1] following the combining pattern of different subsystem variants (e.g., 30 variants available for TMS)
- Supported SC1 with variant subsystem modeling so that **existing models could be reused** (primarily achieved through consistent interface definition)
- Includes a SysML model, where "Executable Stuff" are the MATLAB workflows (i.e., the capability can be utilized from either MATLAB/Simulink only or through a MagicDraw SysML model with the simulation plugin) (SC3 and SC5)

[1] Herber, Dierker, and Patnaik 2023

4

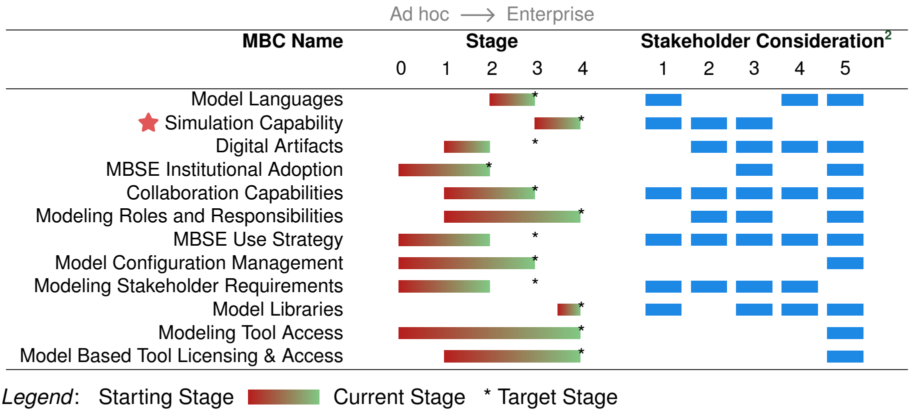
Self-Assessment Based on INCOSE MBCM Capabilities

Self-Assessment Introduction

- Now we summarize the self-assessment of select MBCs
  - 12 MBCs were assessed in detail (see next slide)
- Not all targets[1] are to reach stage 4

[1] Typically means the entire enterprise, which is well beyond the group's reach and resources

→ Self-Assessment of Select Model-Based Capabilities (MBCs)



[1] Please see the paper for discussion on each MBC [2] See Slide 14: [SC1] Reusability and agility [objective], [SC2] Communicate and share [objective], [SC3] Perform effectively *[constraint]*, [SC4] DE strategy standardizes [objective], [SC5] DE strategy works within *[constraint]*

→ Discussion for MBC ★ *Simulation Capability* (3 → 4, *4)

- The M&S team was already predominantly on the cutting edge of simulation capabilities for their specific engineering domain within MATLAB/Simulink
- Significant discussions and pilot efforts were explored to understand better what capabilities should be more MBSE-enabled
- *PT-GRA* in Slide 24 directly highlights the metamodel developed to support executable SysML capabilities and general shareable capability descriptions (SC2)
- Decisions were made to **balance an acceptable amount of fidelity and computational efficiency** (SC3) with new reusable and agile forms (SC1)
    - For example, Capability 1 *PT-Sizing* was linked with MBSE artifacts only, while Capability 2 *PT-System-Analysis* was linked to MBSE artifacts and also made executable from a SysML model
- Overall, an effective process has been defined to enable new and old simulation capabilities in the context of MBSE tools

→ Summary of the Self-Assessment

- Summarizing, two MBCs (Simulation Capability and Model Libraries) were assessed at an already advanced stage for this M&S team, and a key emphasis was to ensure no regression on these MBCs (SC3 and SC5)
  - Some pilot efforts resulted in worse simulation times and inaccuracies
- Most of the remaining assessed MBCs started at low stage numbers (0 or 1) and rose significantly
  - Especially in the areas of Model Tool Access, Model Based Tool Licensing and Access, Model Configuration Management, and Modeling Roles and Responsibilities
- The M&S team will continue to consider what end stages are appropriate for the various MBCs due to resource limitations, alignment with current goals, and enterprise-level consensus being needed

5

Conclusions and Future Work

→ Summary

- In this paper, the physics-based M&S team context and key stakeholder consideration for a targeted DT of their capabilities and digital ecosystem were discussed
- The key aspects of the ongoing DE strategy and digital ecosystem were then described
- Then, self-assessment based on the INCOSE Model-Based Capabilities Matrix (MBCM) was performed on 12 of the 42 MBCs
  - Many showing significant improvements (e.g., $0 \rightarrow 4$ for Modeling Tool Access) or continued effectiveness (e.g., Model Libraries remaining at stage 4)
  - Furthermore, 3 MBCs (Digital Artifacts, MBSE Use Strategy, and Modeling Stakeholder Requirements) still have higher stage targets than are currently assessed and represent targeted future work in the DT

→ Observed and Long-Term Expected Outcomes

- Some of the currently observed and long-term expected outcomes of meeting the stakeholder needs for this M&S team include:
  - **Ability to explore and respond** to a wider range of potential aircraft technologies and solutions, faster and with better assessment capabilities (e.g., with Capability 2 *PT-System-Analysis* for different aircraft configurations)
  - **Better collaboration with other disciplines** regarding PT aircraft concerns and modeling and design capabilities (e.g., with Capability 1 *PT-Sizing* describing sizing capabilities for potential external collaborators)
  - **Less rework and better management** of requirements, models, processes, and capabilities as a whole

➞ Key Future Work Areas

- As the DT is a continued effort, some observed challenges for fully realizing the objectives include continued:
  - Focus on highest impact and immediate needs for the DT of current organizational capabilities
  - Standardization of terminology, models, and processes (e.g., style guides, MIL-STDs, and other reference architectures)
  - Training on the SE and other previously untapped digital ecosystem tools and languages for (non-SE) team members

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Questions?

Integrating Digital Engineering Needs into Physics-Based Modeling and Simulation for Aircraft Power and Thermal Systems

Paper # 343

Daniel R. Herber
Dominic Dierker
Brian Raczkowski
Nathaniel J. Butt
Soumya S. Patnaik

Connect with me at ✉ daniel.herber@colostate.edu

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