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Phased Demonstrations of MBSE in Small Demonstration Satellite Series: Development of System Model and Environment for Full Application of MBSE

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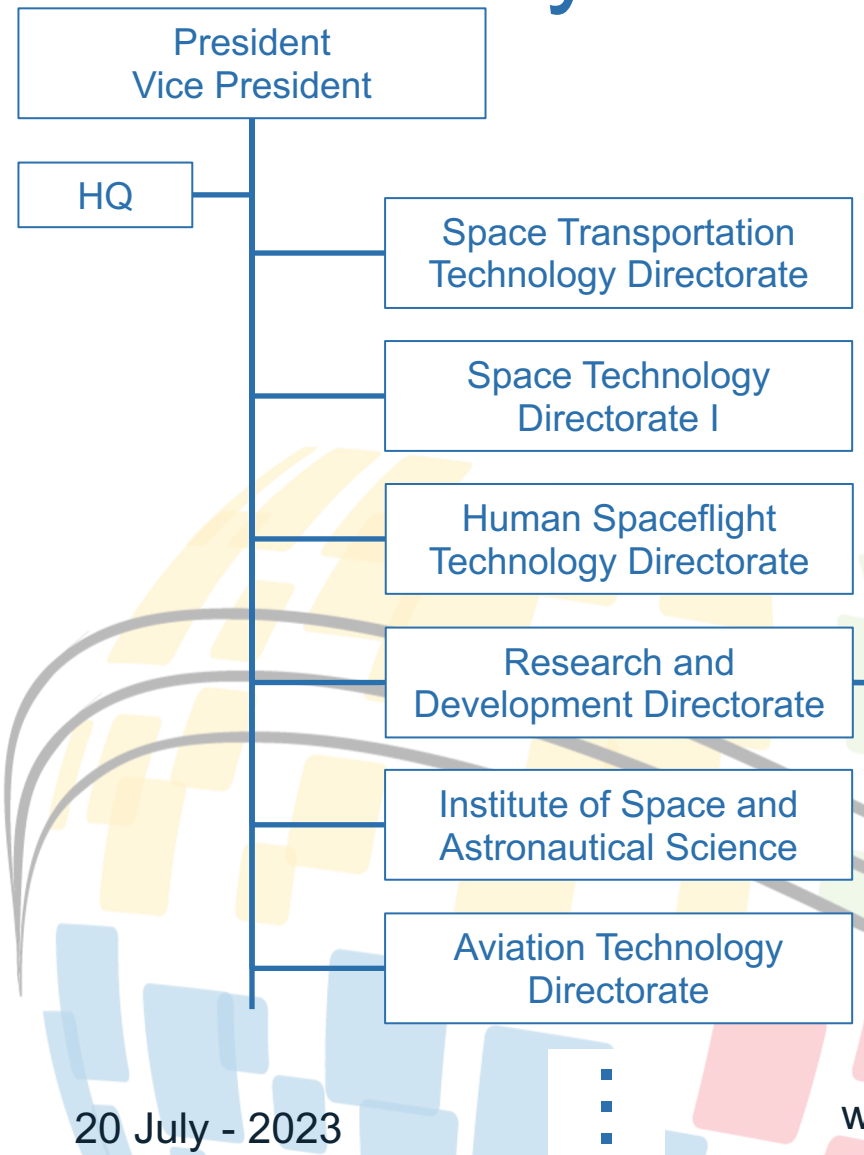
JAXA

Contents

1. Introduction (JAXA STU's MBSE Research approach)
2. Phased Demonstration Strategy for MBSE Application Research [~2019]
3. Partial Application of MBSE to RAISE-3 development [2019-2022]
4. Efforts toward Full Application of MBSE [2021-]
5. Summary

Introduction

Japan Aerospace Exploration Agency System Technology Unit (STU)



JAXA's goal

- Create valuable and competitive space missions
- Execute projects without fail with constructing proper partnership with industry

Organizational Objective of STU

Enhance and strengthen early-phase studies of spacecraft development

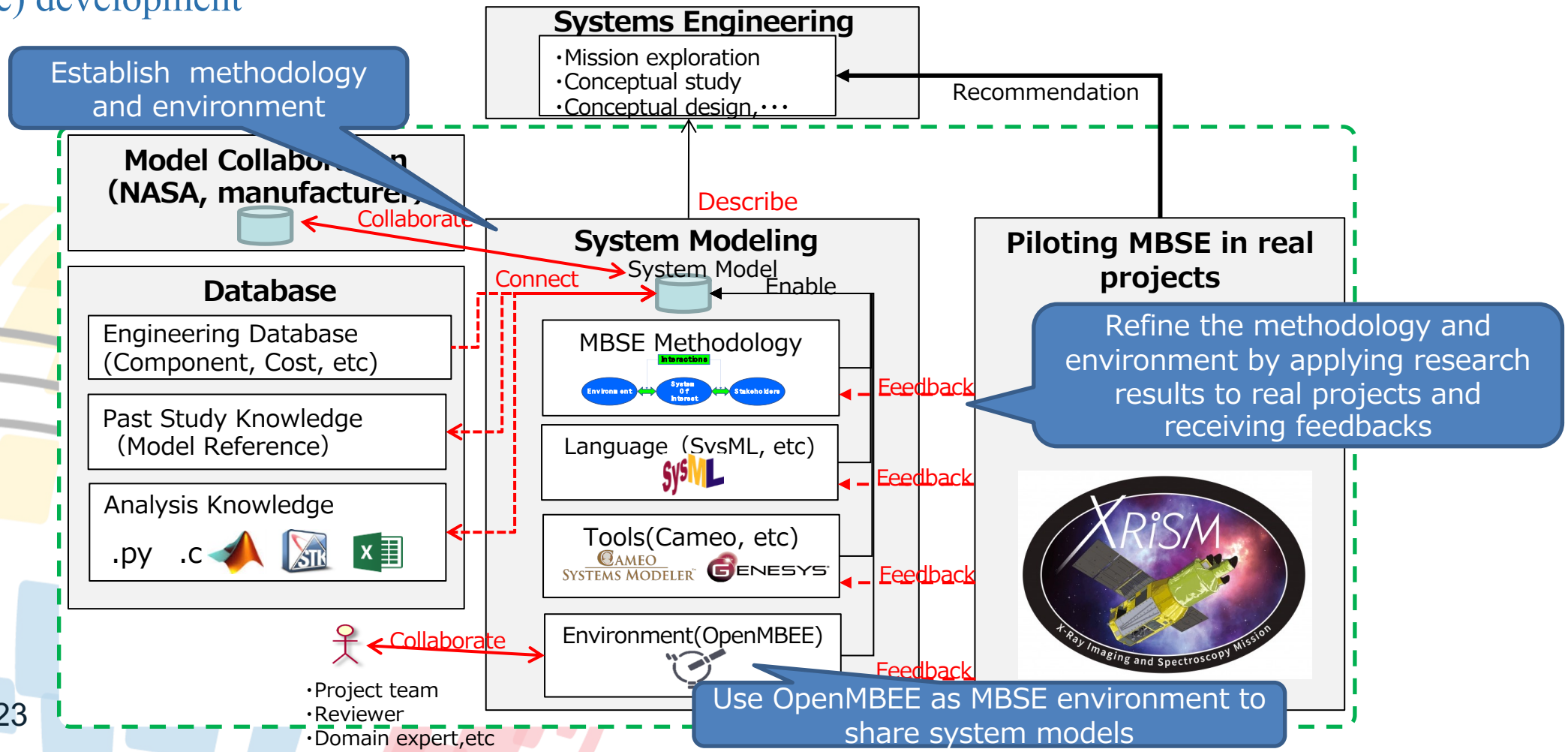
- Generate early-phase study results
- Improve the early-phase study process

Research Approach

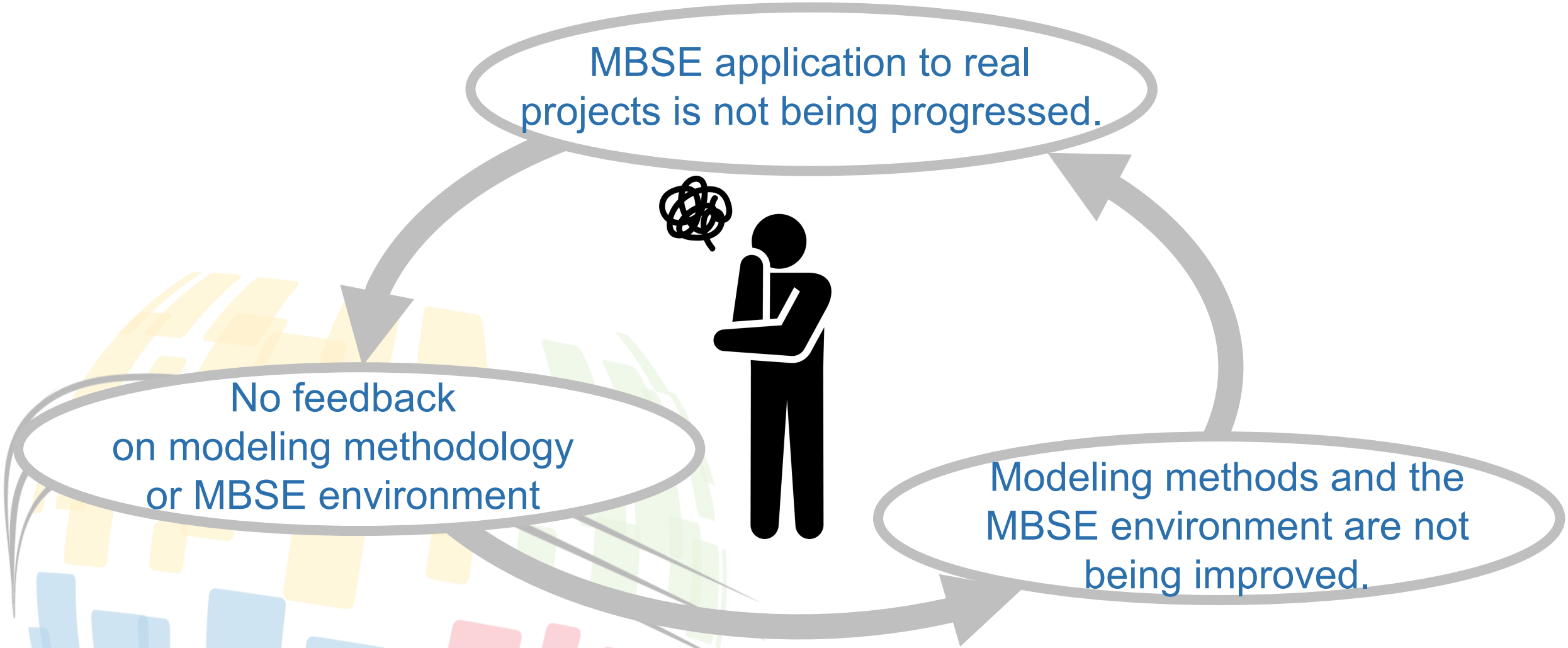
- Conduct early-phase mission study
- MBSE research

MBSE Research in STU

- History
  - 2016 : Started research on MBSE application at JAXA STU
  - 2017 : Built MBSE methodology to apply MBSE to early-phase design
- Our major scope of MBSE research: Building methodology and environment for spacecraft (mainly satellite) development



Our Concerns [~2019]



Phased Demonstration Strategy for MBSE Application Research

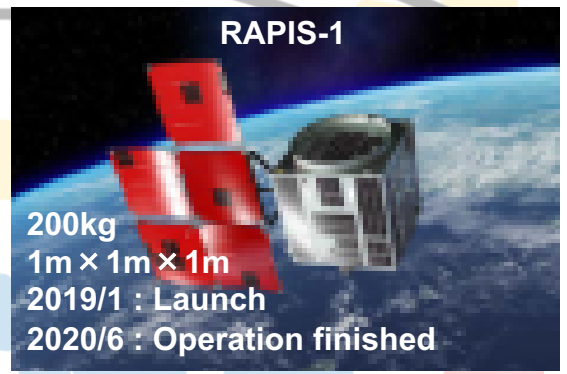
Rapid Innovative Payload Demonstration Satellite (RAISE) Series

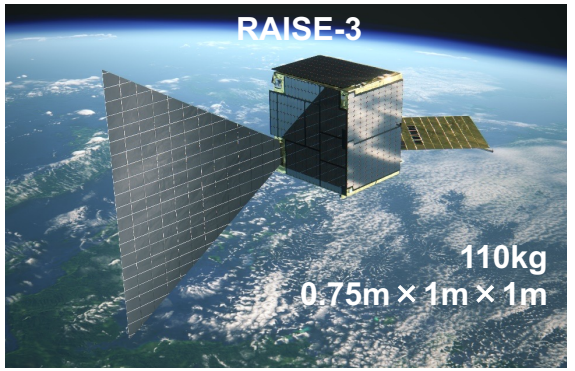
Innovative Satellite Technology Demonstration Program :

- To provide on-orbit demonstration opportunities for new technologies, new key-components and technologies leading to new businesses.
- At least eight demonstrations were planned every two years in accordance with the government's Basic Plan on Space Policy, and three of them were launched.

Rapid Innovative Payload Demonstration Satellite-series :

- Demonstration themes selected for the "Parts, Components and Subsystems" category of the program will be installed in small demonstration satellites developed by JAXA project team for on-orbit demonstrations.





Phased Demonstration Strategy of MBSE Application

- STU, in collaboration with the Innovative Satellite Technology Demonstration Program, has developed a step-by-step MBSE demonstration strategy for real projects. [~2019]

Feature of RAISE series

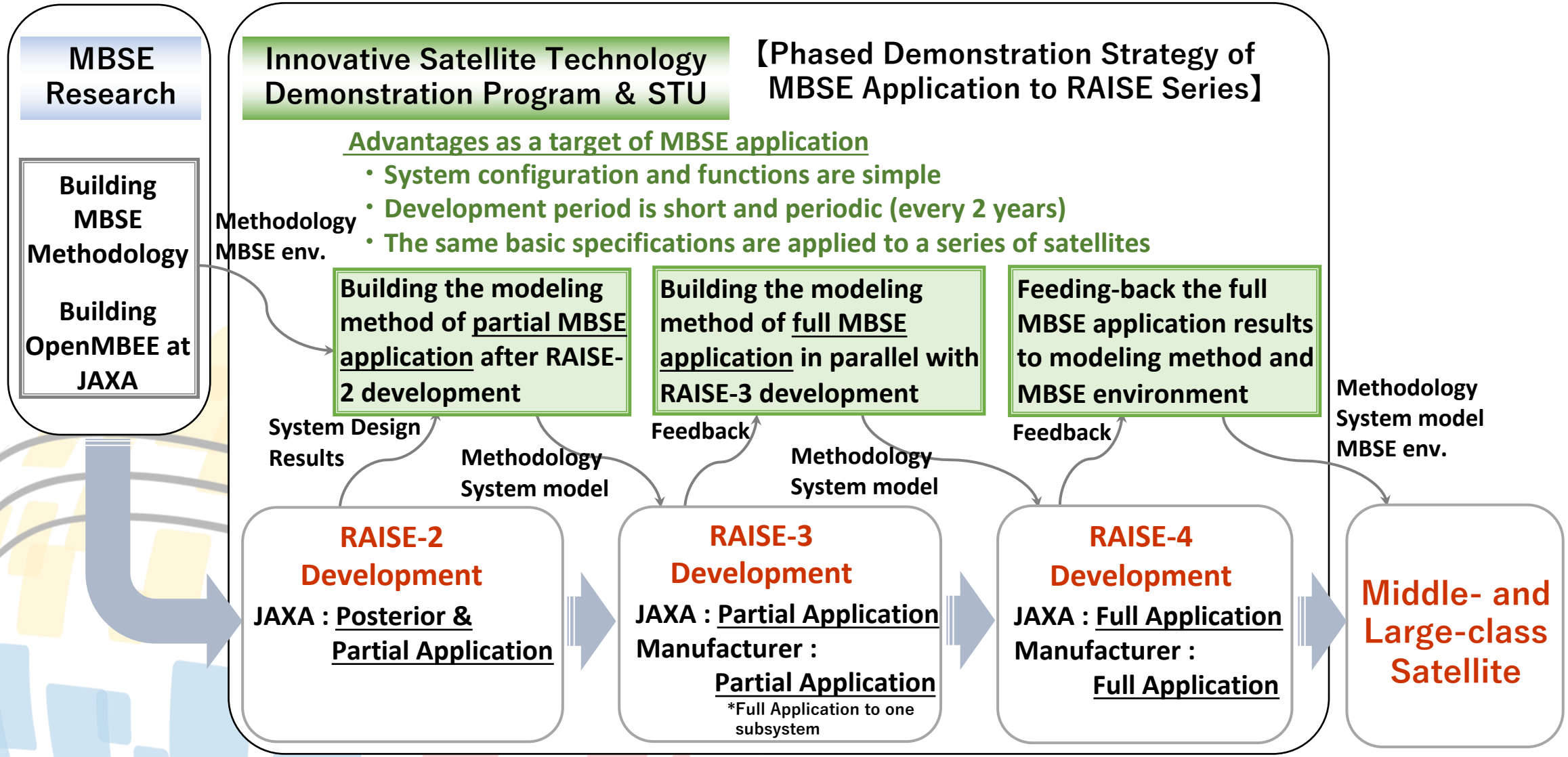
① Satellite size is small, and configuration and function are relatively simple.
② Development period is short and developments are periodic (2 years).
③ The same basic specifications are applied to a series of Satellites

Advantage as a demonstration target of MBSE application

① No need for complex models, allowing us to focus on the methodology of system model building
② Short-term demonstration and frequent feedbacks are possible
③ Similarity makes the system model highly reusable and suitable for step-by-step demonstration

- Approach of phased demonstration
  - RAISE-2 ⇒ RAISE-3 ⇒ RAISE-4
  - Methodologies for applying MBSE are gradually becoming more sophisticated (Partial application ⇒ Full application)
  - Target of MBSE application is not only JAXA's requirement definition process but also Manufacturer's process

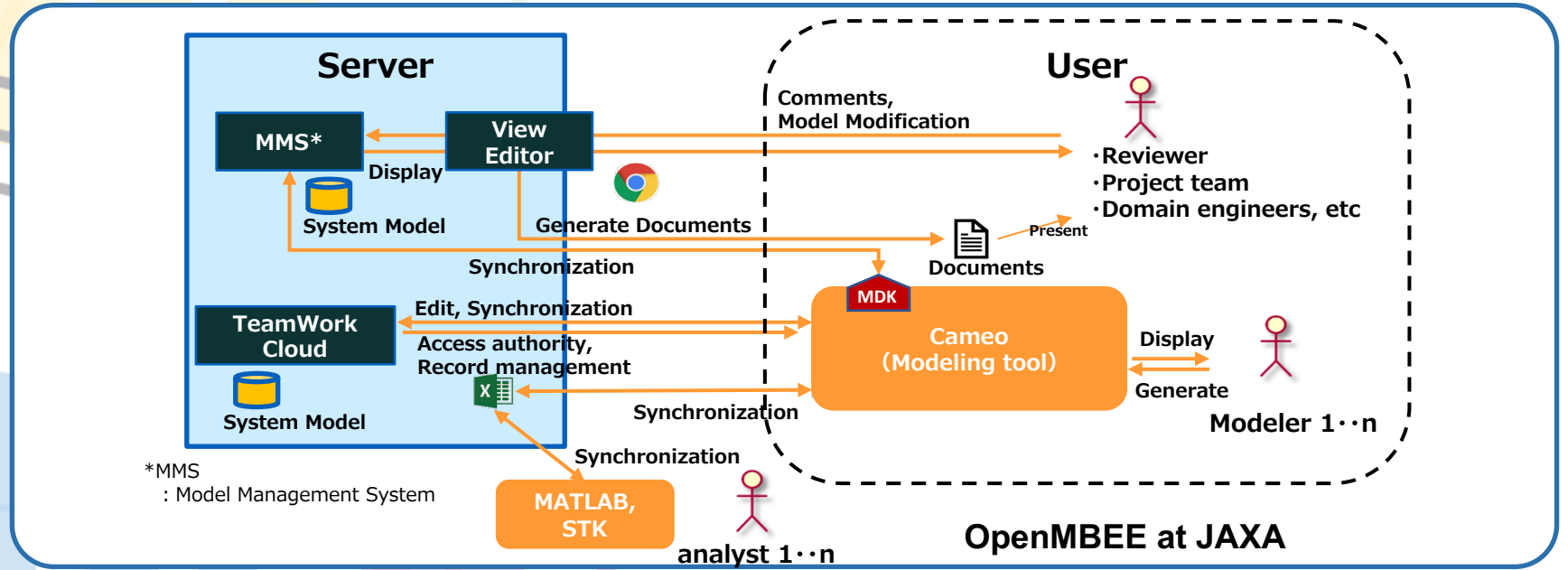
Phased Demonstration Strategy of MBSE Application



Partial Application of MBSE to RAISE-3 Development [2019-2022]

OpenMBEE (Open Model-based Engineering Environment)

- MBSE environment:
  - Various MBSE tools can access information managed as single source
  - View Editor generates documents from system models on web browser
- Advantages of OpenMBEE:
  - Ability to share diagrams and documents generated from system models with project team members and reviewers on web
  - Ability to generate document views from system models by using user-defined document formats
  - Open Source Software (Users can expand functions by themselves)

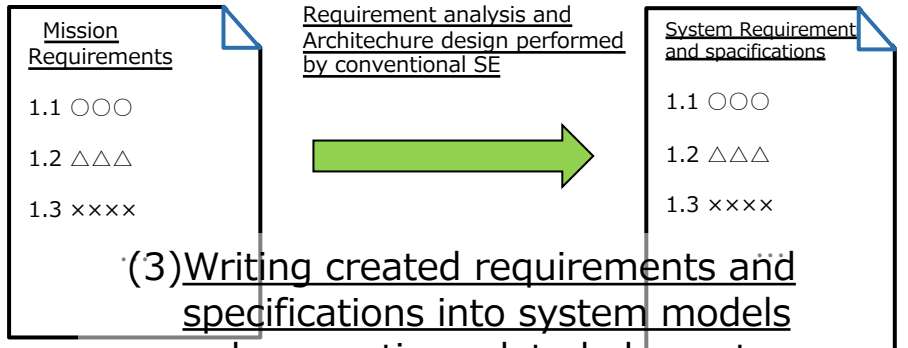


Partial Application of MBSE

- Generate review documents from system model in OpenMBEE （Concept study/Conceptual design phases）
  - We built system models with the method developed by RAISE-2 activity, in which we confirmed system model's structure to generate review documents with OpenMBEE.
  - We generated document views from the system models and presented document views directly to reviewers of review board using OpenMBEE.

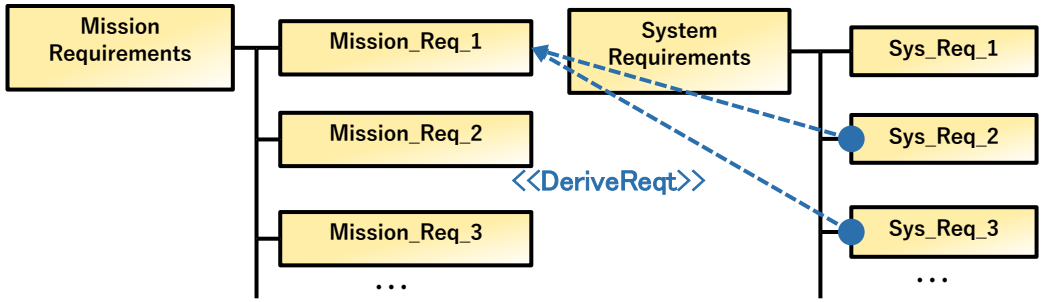
Requirement Analysis Process from Mission Req. to System Spec.

(1)Clarifying high-level requirements by document-based SE



(2)Deriving system requirements and specifications by document-based SE

(3)Writing created requirements and specifications into system models and connecting related elements



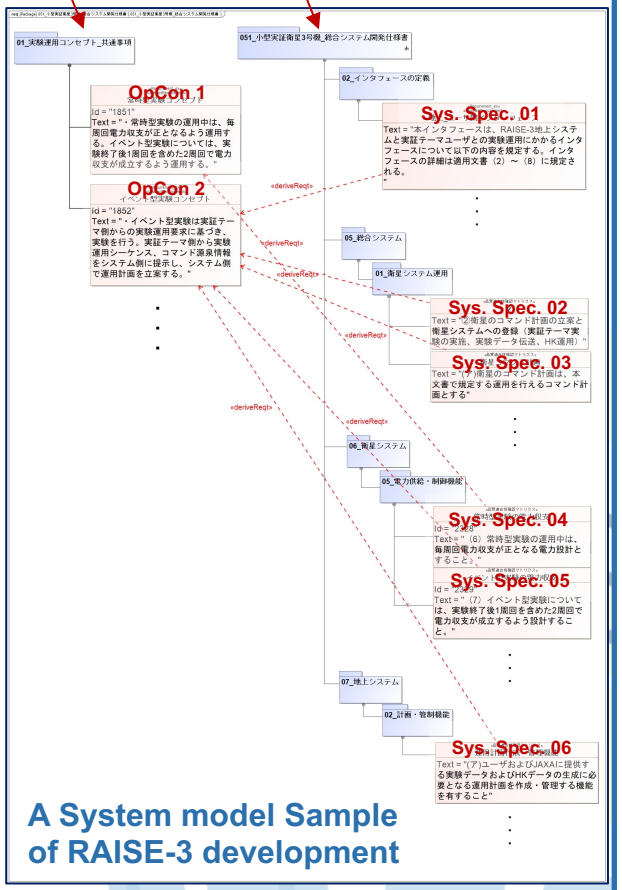
Concept of our modeling method we applied to RAISE-3 development (partial MBSE application)

Document Views on OpenMBEE

- OpenMBEE enables us to generate document and table views from system model. These views are comparable to conventional SE products.

Operational Concept Folder

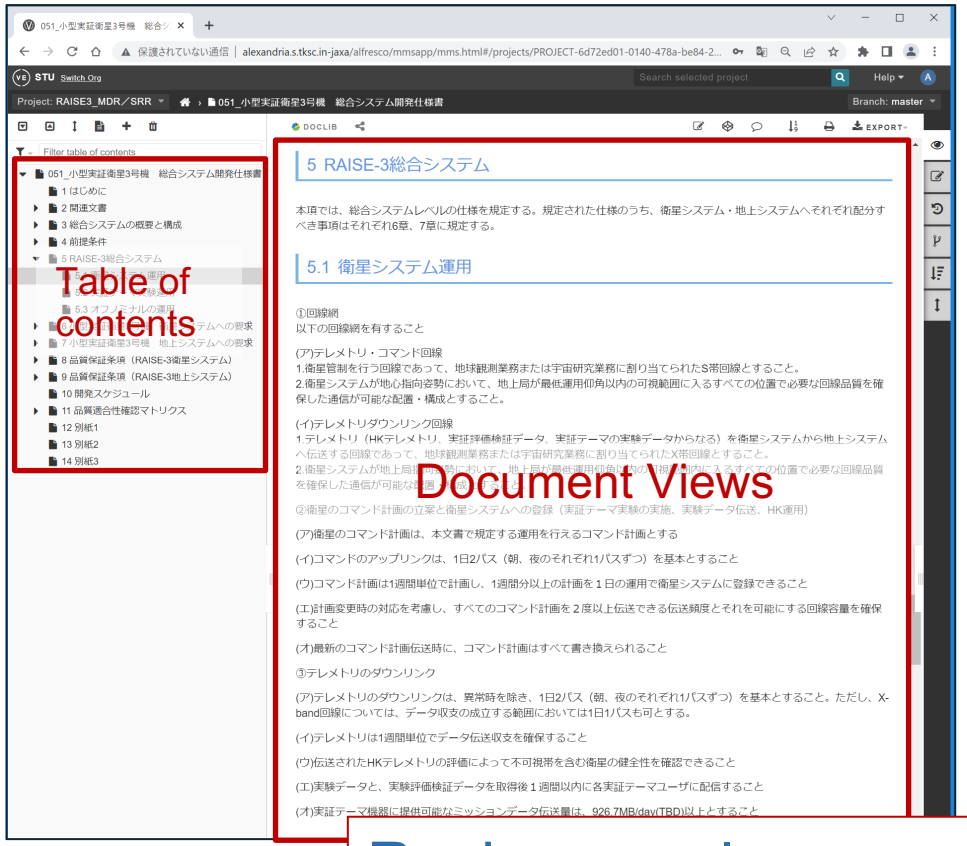
System Specification Folder



A System model Sample of RAISE-3 development

- Views on VE(OpenMBEE)

【Document Views (RAISE-3 System Specifications)】



【Table Views (Traceability from Operational Concept to System Specifications)】

Operational Concept

System Specification

ICS = Interface Control Specification

Rationale

Table 1. 表3-1 上位文書と下位文書の対応表

運用コンセプト	総合システム開発仕様書	ICS	トレーサビリティ根拠
・実証テーマ側で実験運用要求を作成するため、システム側より定期的に軌道情報を提供する。	7.3.1 軌道力学系機能 （1）衛星システムからのGPSRデータを用いて軌道決定ができること。また、その軌道決定値を用いて、運用に必要な軌道情報（衛星軌道予測、アンテナ予報値等）が作成できること。 （2）2週間後までの軌道予測、地上局可視解析が実施できること。また、それらの情報を必要とする実証テーマに提供できること	N/A	MIMOチャネル推定実験Activity(衛星管制システム/地上局#1) D2-LEOMI-1 MIMOチャネル容量実験Activity(衛星管制システム/地上局#1) D2-LEOMI-2
・実証テーマ側で軌道情報とMIMO地上局の位置を考慮し、実験運用シーケンスを立案する。	N/A	LEOMI:5.2 作業分担 表5.2-1 No22	MIMOチャネル推定実験Activity(LEOMI実験システム#1,2,3) D2-LEOMI-1 MIMOチャネル容量実験Activity(LEOMI実験システム#1,2,3) D2-LEOMI-2
・MIMO送信時には、衛星システムの姿勢制御により、衛星のMIMOアンテナをMIMO地上局（通信対象となる複数の地上局の中心位置）へ指向させる。	6.1.4 姿勢制御機能 （5）D-SAIL展開後の外乱トルクを補償し姿勢制御するため、リアクションホイール1台あたりの最大角運動量を0.3Nms以上、磁気トルカの1台当たりの発生磁気モーメントを$15Am^2$以上とすること	N/A	MIMOチャネル推定実験Activity(パス機器#3) D2-LEOMI-1 MIMOチャネル容量実験Activity(パス機器#4) D2-LEOMI-2
・衛星上のMIMOアンテナからMIMO地上局に向けてSISO伝送ないしは複数アンテナを用いたMIMO伝送を行う。	N/A	LEOMI:11.1 概要 表11.1-1 実験モード #1,2 LEOMI:11.2 運用区分 表11.2-1	MIMOチャネル推定実験Activity(ミッション機器#1) D2-LEOMI-1 MIMOチャネル容量実験Activity(ミッション機器#1,2) D2-LEOMI-2

Reviewers also supported this activity !

MBSE Application Activity with Manufacturer (1/2)

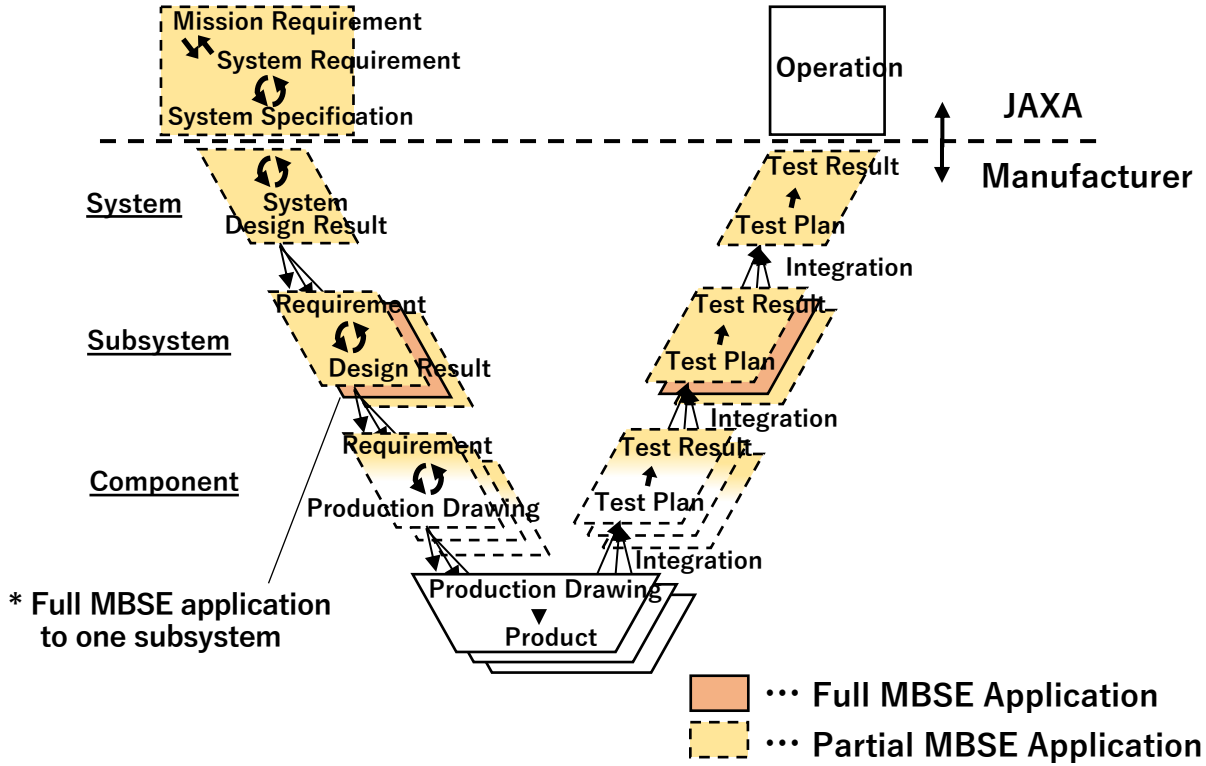
- RFP for trial activities to apply MBSE to RAISE-3 development
  - In order to expand MBSE trial activity to design and production phase, we added optional requests to RFP for selecting a system manufacturer/integrator of RAISE-3 development.

RAISE-3 technical assessment items:
Application of MBSE and centralized management of design and verification information by using system models

(1) Building MBSE environments to share system models with JAXA and manufacturer
(2) Building system models in which design and verification information are traced to JAXA's requirements model (*)
(3) Building efficient method to confirm traceability by using system models generated by (2)
(4) Trial to optimize preparation and operation of review board activity by using system models
(5) At least for one subsystem, performing requirement analysis and architecture design by model-based approach (not by conventional approach) to determine subsystem and component specifications

* JAXA's system model contains mission requirements, conceptual operations, ICS and system specifications

<Agreements with manufacturer through RFP>
As the results of RFP, MHI (Mitsubishi Heavy Industries, Ltd) was selected as system integrator. About MBSE requests, Agreement with them is following.
- They will address (1)-(5) terms above.



【MBSE Application Scope to RAISE-3 Development】

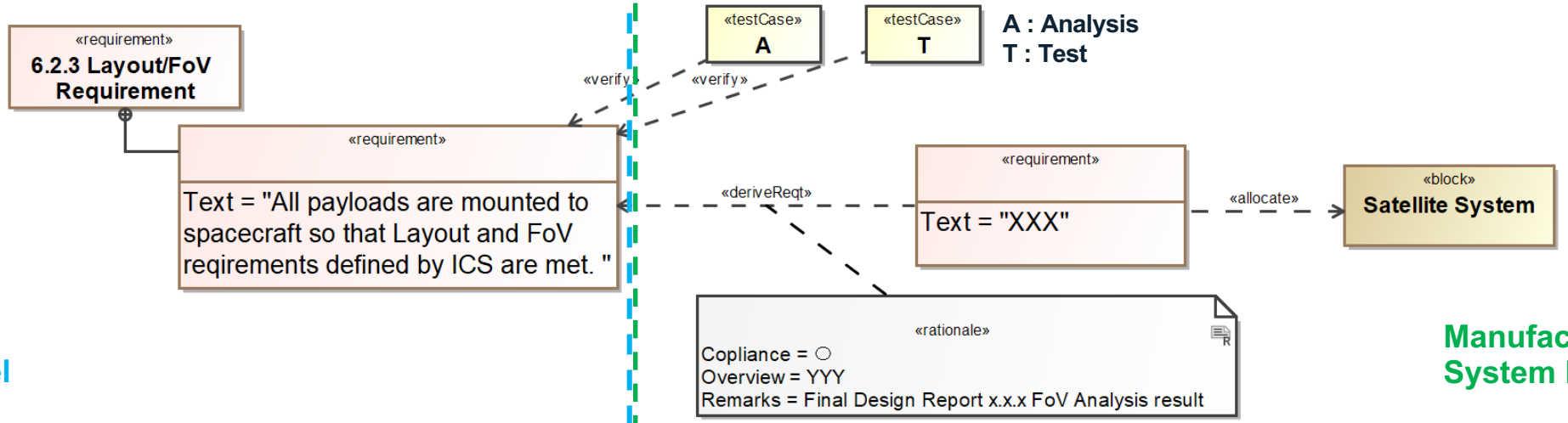
MBSE Application Activity with Manufacturer (2/2)

- Building system models to confirm traceability （Basic/Detailed Design Phase）
  - In design phase, JAXA and the manufacturer built system models together in order to confirm traceability from system requirements of JAXA to designs, V&V plans and results generated by the manufacturer.
  - In CDR, project team and STU presented compliance matrix and verification matrix generated by system models. We intended to generate same matrices as conventional SE products for reviewers' convenience.

Appearance of Compliance Matrix

No.	JAXA's Specification		Allocation	Verification Method	Design Result	Compliance Assesment		Remarks
	Term	Text				Compliance	Overviews	
1	6.2.3 Layout/FoV reuqirement	All payloads are mounted to spacecraft so that Layout and FoV reqiurements defined by ICS are met.	Satellite System	A, T	XXX	○	YYY	Final Design Report x.x.x FoV Analysis result
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Structure of System Model



Concept of Building Compliance Matrix

RAISE-3 Activity Summary

- We started to apply MBSE from concept study/conceptual design phases, based on trial results of posterior MBSE application activity to RAISE-2 development.
- From basic design phase, we applied MBSE with a manufacturer.

MDR/SRR (‘20.8) → SDR (‘21.2) → PDR (‘21.5) (Only manufacturer side) → CDR (‘21.12~‘22.4) → PQR (’22.8)

	Concept Study /Conceptual Design	RFP	Basic Design	Detailed Design	Production
JAXA	• **Generating and Managing review documents in OpenMBEE** • Building analysis tools connected to system models	• **RFP for trial MBSE application activities** • Improving OpenMBEE (Presentation of backward traceability / Trial of connecting OpenMBEE to JAXA review board support system)	• Proposing system specifications by using system models • Improving OpenMBEE (release of keyword search function in multiple document views on OpenMBEE) • Discussing system models’ structure to confirm traceability from JAXA’s specification to manufacturer’s design and V&V activities • Supporting manufacturer to build their digital review board environment using OpenMBEE		
Manu-facturer		• **Proposing for RFP**	• **Building their digital infrastructure and MBSE environment including OpenMBEE** • Discussing their system models’ structure and ontology	• **Building system models to confirm traceability from JAXA’s specification to manufacturer’s design and V&V activities** • Performing SE processes for thermal subsystem by model-based approach	• Managing traceability of V&V results by system models

MBSE Application Plan Revised

- Epsilon rocket carrying RAISE-3 failed to launch in October 2022.
- JAXA decided to develop a satellite with almost the same specifications(*) as RAISE-3 and to name it RAISE-4.
- Since the specifications are almost the same and the development period is short, the RAISE-4 project team and STU decided not to make major changes to the SE methodology from RAISE-3 development.
- MBSE Application Plan Revised
  - The target of full application is changed from RAISE-4 to RAISE-5
  - In RAISE-4 development, the methodology prepared for full application will be applied only to changes implemented with respect to RAISE-3.

*… Of the seven demonstration equipments installed on RAISE-3, six will be installed on RAISE-4 and two new equipment will be added.

Efforts toward Full Application of MBSE

Approach of Full MBSE Application

System model for RAISE-3 (Partial MBSE application)

A system model was created after defining requirements (e.g., MRD, SRD) based on conventional (document-based) SE process.

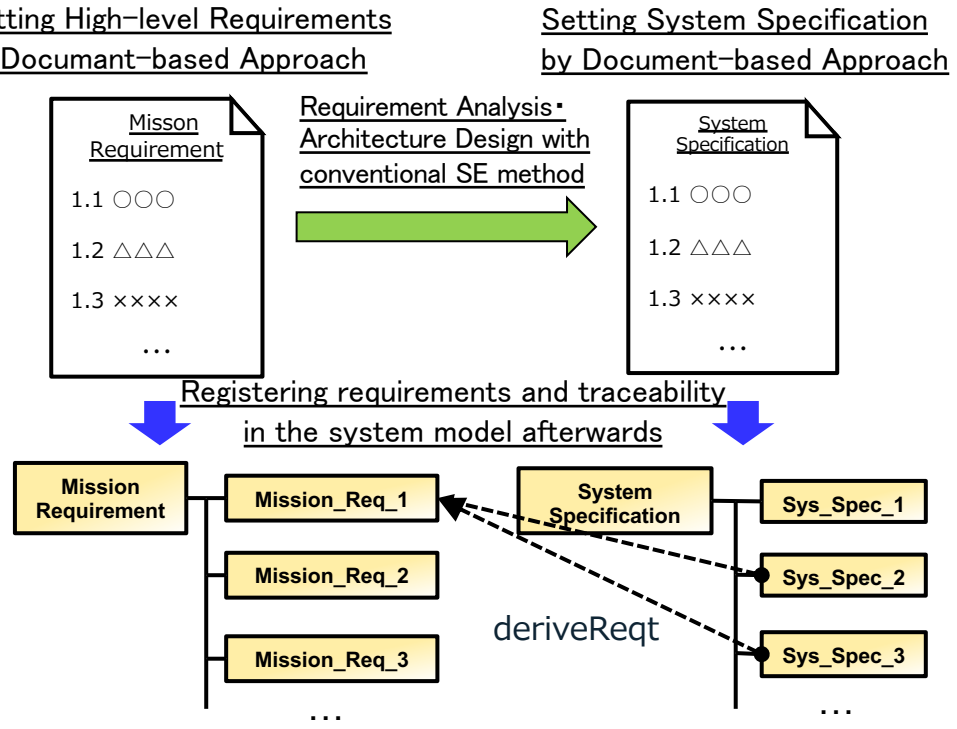


Image of the system model (Model Centered on Requirements)

System model for RAISE-5 (Full MBSE application)

All artifacts of SE processes (e.g., requirement, behavior, structure) are represented and managed on a system model by fully utilizing a model from early phase of SE processes.

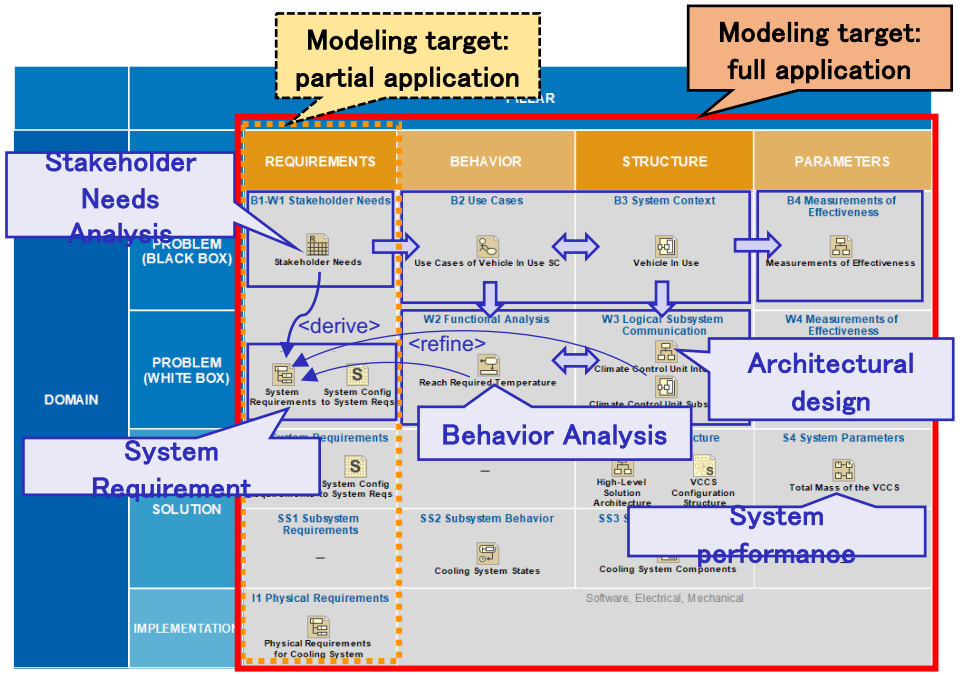
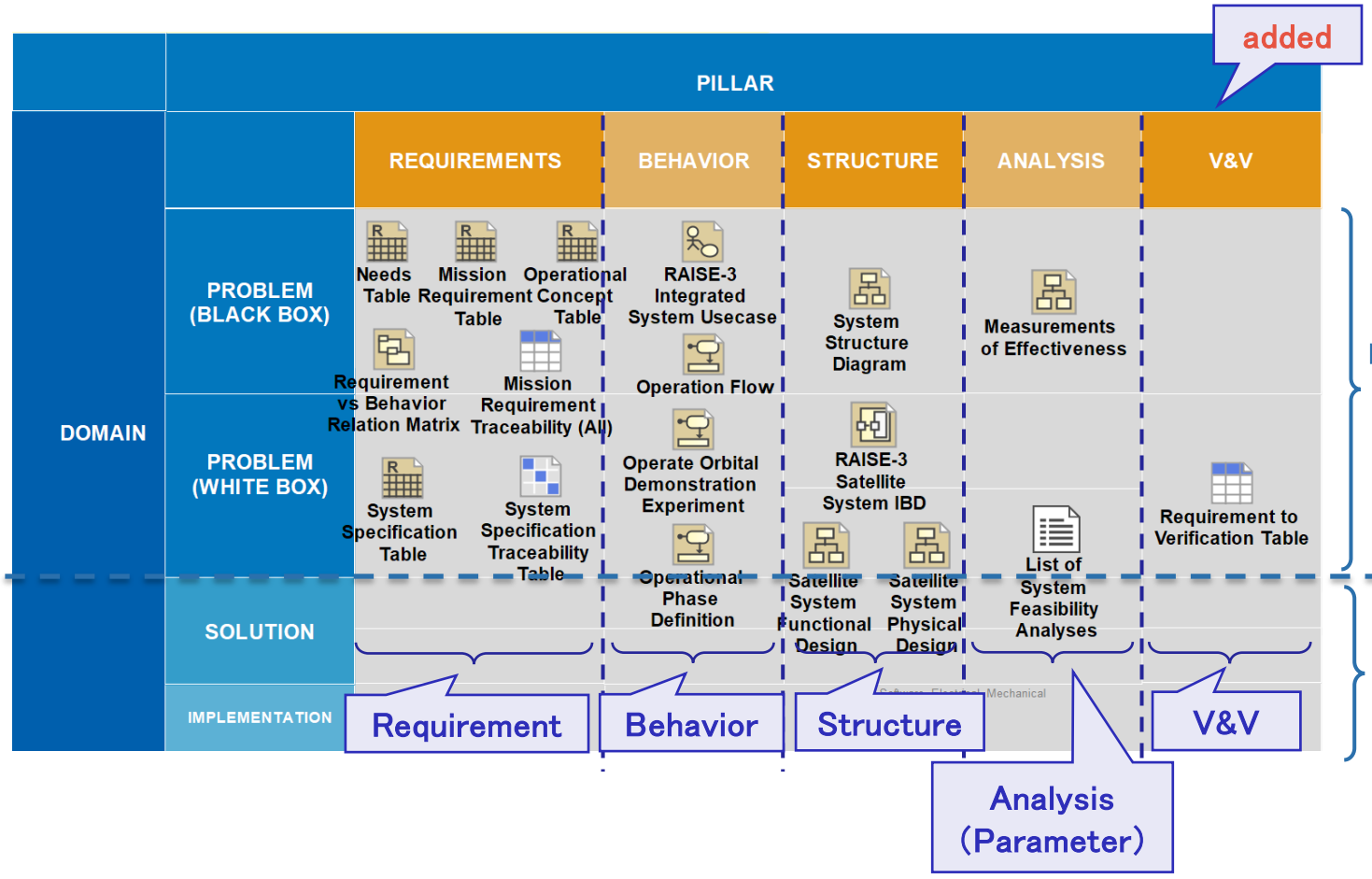


Image of the system model (Model contains various information of SE process with model-based approach)

Framework for Full Application

- Based on the "MagicGrid" framework proposed by No Magic, we built a framework that will be used in our full application of MBSE.



The client (JAXA) builds a system model for the Problem Domain (up to the system specification definition) and presents it to the manufacturer.

The manufacturer builds a system model in the Solution Domain and below (design, verification, etc.) to conform to the client's system model, and presents it to the client.

Building System Model

- Based on approach and framework shown in previous slides, modeling method is being developed for our full application of MBSE in future RAISE-5 development (mainly in the Problem domain, which is JAXA's responsibility)
- The SE process (from stakeholder needs analysis to system development specification definition) was decomposed into 20 processes, and the modeling process and outputs were organized.

- Black Box Analysis Process

(a) Stakeholder Analysis
(b) Stakeholder Needs Analysis
(c) Context Analysis
(d) Use Case Analysis
(e) Value-Creation
(f) Mission Requirement Definition
(g) Operational Concept Definition (part 1)
(h) MoEs Definition

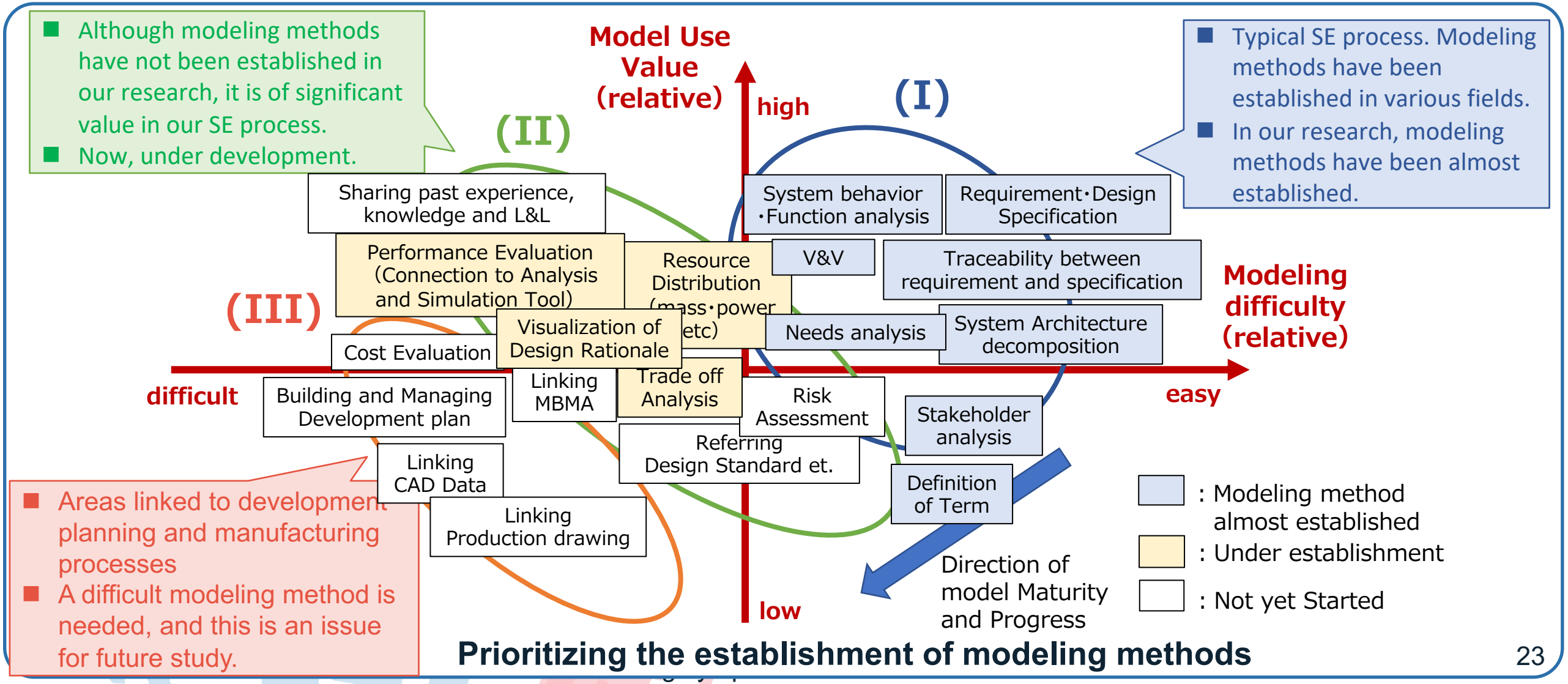
Please see our paper for detail.

- White Box Analysis Process

(a) Operational Phase and Operational Scenario Definition
(b) System Behavior Analysis in each Operational Scenario
(c) Allocation of MoEs to each Component (Part 1)
(d) Interface Definition (Part 1)
(e) Operational Concept Definition (Part 2)
(f) Internal System Behavior Analysis
(g) Functional Requirements Definition
(h) Allocation of MoPs to each Component
(i) Non-functional Requirements Extraction
(j) Interface Definition (Part 2)
(k) System Specification Definition
(l) Coverage Check from High-level Requirements

Modeling Scopes and Objectives

- Modeling all information in the SE process down to detail would require a large amount of resources.
- Need to select modeling targets based on the use value of the model to achieve higher quality and efficiency in SE

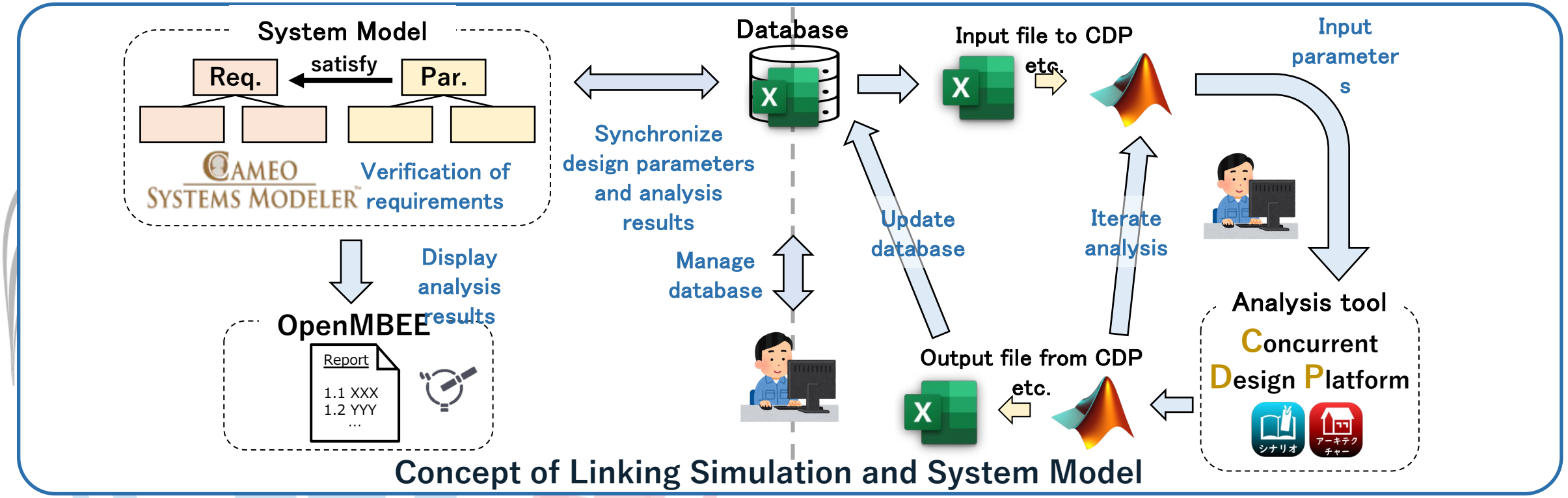


Remaining Issues for RAISE-5 Development

- What we aim to achieve by applying MBSE
  - System Requirements are derived from high-level SE processes (i.e., Stakeholder Needs, Mission Requirement) with consistent traceability
  - Formalization and reuse of SE processes using the system model could contribute to speeding up and de-personalizing the concept studies/designs (e.g., needs analysis to specification definition)
  - Describing background information and rationales in a system model could prevent misunderstanding between stakeholders (e.g., JAXA and manufacturer)
- What are the remaining issues for the next step
  - Need to define appropriate granularity and layering of model elements (e.g., requirements, behaviors) corresponding to each system level (e.g., integrated system level, satellite system level, satellite subsystem level)
  - Need to further update methods for setting up appropriate "views" and extracting necessary information from the model
  - Need to incorporate various trade studies in a system model
  - Need to connect a system model with analyses (see next slide)

Linking System Model with Simulation

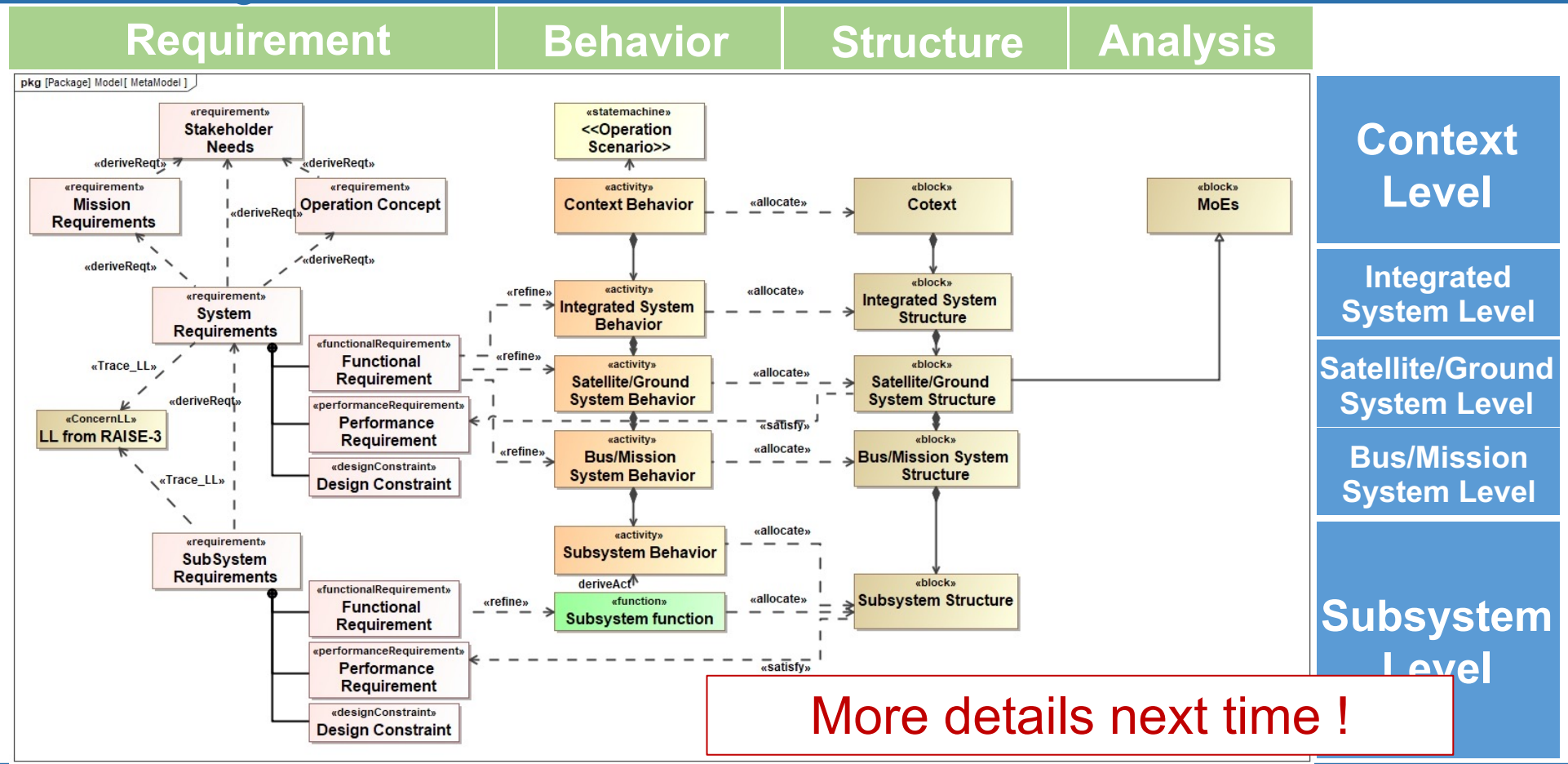
- To achieve better systems engineering activities using MBSE, collaboration with analysis and simulation technologies is an important issue.
- By centrally managing system models and parameters used in the analysis and simulation environment via a database, we built an environment that enabled rapid evaluation of the feasibility of design results in relation to requirements
- We will apply this environment to RAISE-5 development.



Concept of Linking Simulation and System Model

RAISE-4 Development Started !

- RAISE-4 MDR was held in February 2023. SDR concluded at July 12th 2023.
- The system specifications for RAISE-4 are mostly inherited from those of RAISE-3, but some specifications are different due to changes in the demonstration equipments in RAISE-4.
- For the specification change, the system model was used in the derivation process of the system specifications according to the following meta-model.



More details next time !

Summary

Summary

- JAXA STU, in collaboration with the Innovative Satellite Technology Demonstration Program, has developed and is implementing the phased strategy to apply MBSE to the development of the RAISE-series satellites.
- The partial MBSE application to the RAISE-3 development was completed successfully.
- Although the launch failure of RAISE-3 caused a change in the MBSE application plan, the methodology is being established and demonstrated in the RAISE-4 development in preparation for full MBSE application to the RAISE-5 development.
- Our MBSE application activities are still under development. We would like to report the results of full MBSE application in next opportunity.

33rd Annual INCOSE international symposium

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Honolulu, HI, USA
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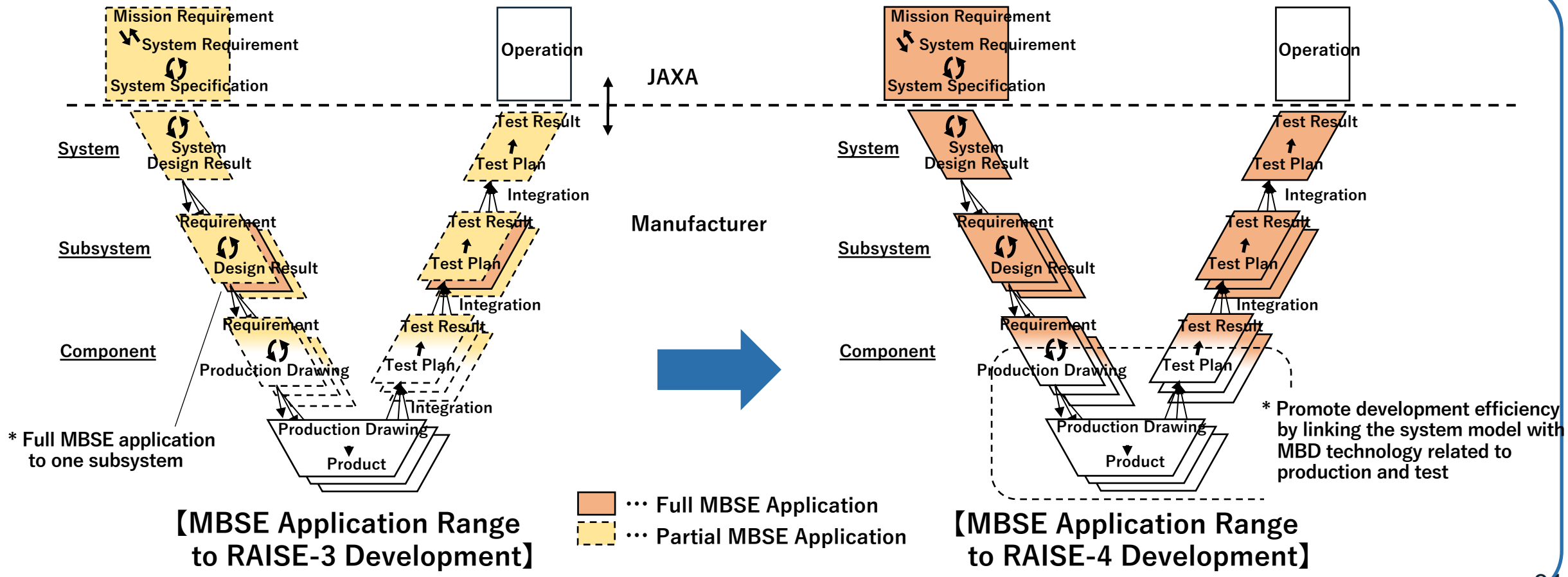
Thank you for your attention.

Backup

MBSE Application Range in RAISE-3 and 4 Development

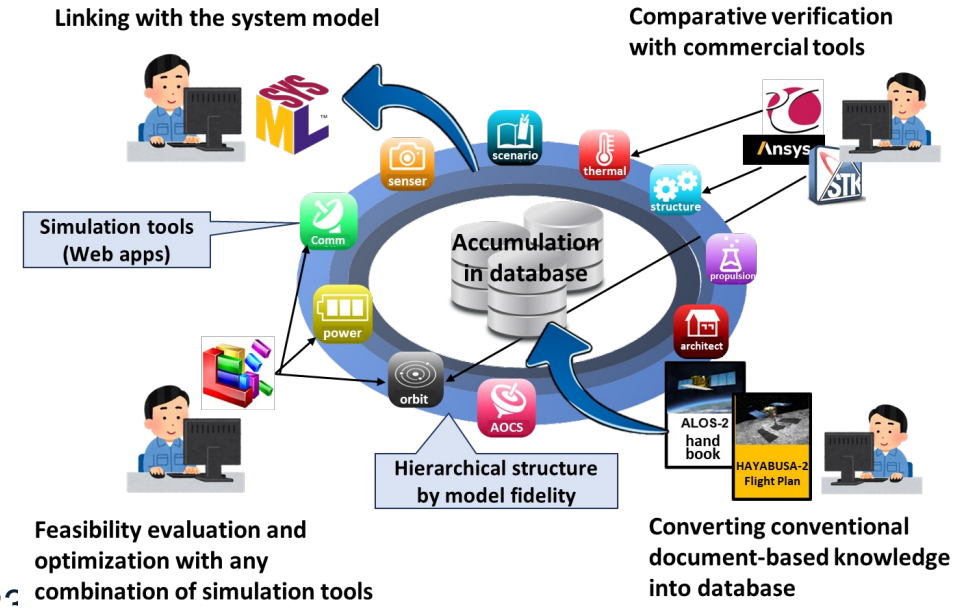
- The scope of application is not limited to the SE process within JAXA, but also includes the SE process within the prime contractor developing the satellite system.
- In the manufacturer process, the target of MBSE application is mainly satellite system level and subsystem level.



Linking the System Model with Simulation (1/3)

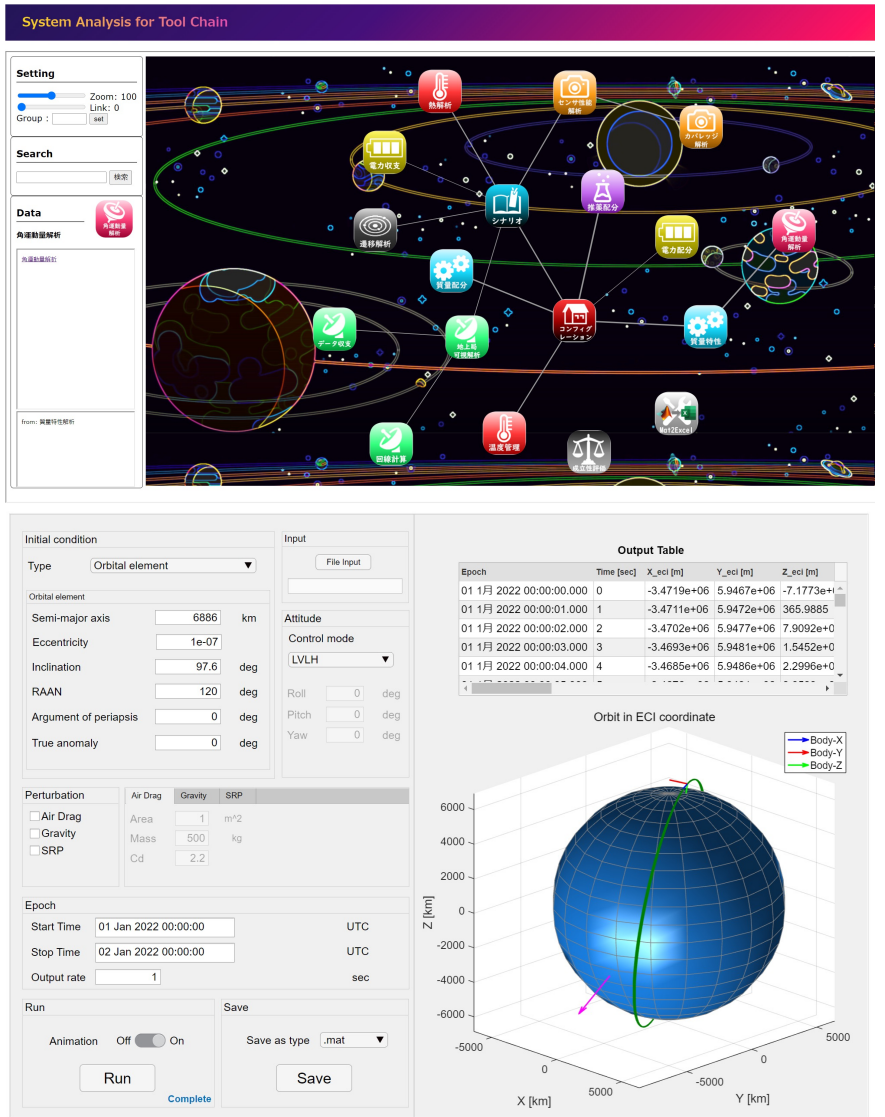
- Background/Issues
  - To achieve better systems engineering activities using MBSE, collaboration with analysis and simulation technologies is also an important issue.
  - JAXA utilizes a variety of analysis and simulation technologies, but the type and fidelity of the analysis used in each phase varies greatly, and consistency across the development lifecycle is not ensured.

- Built the Concurrent Design Platform, a design analysis tool for seamless implementation of various system analyses, taking into account with fidelity control and affinity with database.



Linking the System Model with Simulation (2/3)

- Approach
  - By adopting MATLAB's Web App Designer as the development environment and making all tools into web apps, users can perform all analysis in a web browser.
  - Algorithm explanations and use cases were manualized for each application to ensure that users fully understand and use the physics they are solving.



Sample of Web apps views (Upper: Home Page、Lower: orbit analysis app)

Linking the System Model with Simulation (3/3)

- By centrally managing system models and parameters used in the analysis and simulation environment via a database, we are building an environment that enables rapid evaluation of the feasibility of design results in relation to requirements, and we are experimenting with more efficient parameter management methods.