MBSE in the High-Tech Equipment Industry

MBSE-Study phase 2 of TNO-ESI and Partners: Key MBSE topics and approaches

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Summary

This report documents the second phase of the MBSE study conducted by TNO-ESI and its partners, focusing on the deployment and added value of Model-Based Systems Engineering (MBSE) in the Dutch high-tech equipment industry. MBSE is increasingly adopted as a means to improve systems engineering effectiveness. By positioning models as the authoritative source of engineering information, MBSE can support the full lifecycle of cyber-physical systems and facilitate collaboration across disciplines and organizations.

Key Observations and Recommendations:

The phase 2 MBSE study was structured around four thematic workshops, each addressing a critical aspect of MBSE deployment in the high-tech equipment industry. The following key observations and recommendations have emerged:

- **Interface-centric MBSE as a pragmatic starting point.** Focusing MBSE efforts on interface management provides immediate value, especially in distributed and brownfield development environments. Modelling interfaces clarifies responsibilities, reduces integration risks, and supports modularity. Early value can be achieved by formalizing and governing interfaces, which also strengthens collaboration with suppliers.
- **Variation management and product line engineering.** Managing product diversity and platform-based development is central to the high-tech equipment industry. MBSE enables configuration management, systematic reuse, and impact analysis across product lines. The adoption of standard updates such as SysML v2 can facilitate consistent product line modelling practices, improve traceability and management of variability throughout the engineering lifecycle.
- **Critical-to-quality (CTQ) modelling and system behaviour.** CTQ properties (e.g. performance, reliability, and safety) are essential for meeting customer expectations and contractual obligations. The study highlights the need to connect descriptive system models with analytical models and simulation tools, enabling early validation and continuous verification throughout development.
- **Organizational embedding and change management.** Successful MBSE deployment requires organizational readiness, strategic alignment, and investment in training, governance, and stakeholder engagement. Pilots addressing concrete business challenges, differentiated training, and internal communities of practice are recommended to build momentum, demonstrate early value, and sustain adoption.

For achieving value with MBSE in complex systems engineering environments, adopting a phased and business-driven approach to MBSE is favoured, supported by incremental implementation and alignment with agile engineering practices. Importantly, MBSE should be seen as an enabler that strengthens both rigorous engineering execution and alignment with strategic product definition: MBSE supports 'designing the product right,' but does not replace the need for technical leadership and sound system architecting nor replaces the need for a deep understanding of business needs and market context.

Next Steps:

Following the completion of phase 2 of this study, a Special Interest Group (SIG) is continuing the initiative, focusing on cross-organisational knowledge exchange, and ongoing exploration of MBSE practices tailored to complex, low-volume system development.

Contents

1 Introduction

In 2020, TNO-ESI was approached by several of its industry partners with questions about Model-Based Systems Engineering (MBSE). TNO-ESI embarked on a study on the value of contemporary MBSE-methodologies for the Dutch high-tech equipment industry, building on their strong tradition of using Model- Driven methodologies to address Systems Engineering challenges. After doing a quick literature scan, TNO-ESI took the initiative to start a joint *MBSE-study* in close cooperation with its industry and academic partners[1] in June 2020. This study ran until December 2021. Observations and conclusions from this study are documented in the report “MBSE in the High-Tech Equipment Industry – Observations and Conclusions” [1] , see also section 4.5.

From 2022 - 2024 the MBSE study continued with four quarterly 2-day thematic workshops addressing the following topics:

1. MBSE and interfaces.
2. Variants & Diversity.
3. Critical to Quality (CTQ) & System behaviour.
4. Embedding and introduction of MBSE.

These topics were discussed with industry in the thematic workshops. This report captures the observations and conclusions resulting from these workshops.

TNO-ESI thanks their partners and the further participants who contributed to this study and its results.

1 Industry partners: ASML, Canon Production Printing, Philips, Thales, Vanderlande Industries, Academic and knowledge partners; Delft University of Technology, Radboud University, University of Amsterdam, University of Eindhoven, University of Twente, other units TNO.

2 Study Overview

2.1 Study charter

The initial phase of the MBSE study (2020-2021) investigated the feasibility and benefits of implementing Model Based Systems Engineering in the high-tech equipment sector. This phase resulted in a report [1] containing the following results of the phase 1 study:

- A comprehensive overview of MBSE trends and developments.
- Insights into the current state of MBSE within the Dutch high-tech equipment industry.
- Identification of key aspects critical to transitioning from traditional systems engineering to an MBSE approach.

In addition to the results and findings of the report [1], participants valued greatly the frank exchange of information and experiences between organisations. During the second phase of the MBSE study (2022-2024) TNO-ESI and its partners continued the joint effort with a more in-depth study centred around four key topics that were identified during the initial phase:

- MBSE and interfaces.
- Variants & diversity.
- Critical to Quality (CTQ) & System behaviour.
- Embedding and introduction of MBSE.

With the aim to provide a structured forum to stimulate information exchange and cross-organisation dialogue, the charter for the second phase of the MBSE study mentioned the following ambition:

We want to:

1. Support industry partners
   Assist TNO-ESI's industry partners in developing their own MBSE transformation and implementation plans.
2. Optimize research roadmap
   Enhance TNO-ESI's research roadmap to:
   a. Utilize available MBSE methods and tools in future research projects.
   b. Focus on MBSE-related research areas that aid in successful MBSE integration.
3. Consolidate and distribute insights
   Share insights and learnings to facilitate the successful adoption of scalable MBSE methods and tools across the high-tech, software-intensive equipment industry.

Therefore, we need to:

1. Understand challenges
   Study challenges, dilemmas, and key points related to the critical topics identified in phase 1.

2. Collaborate for actionable Plans
   Determine how industry and TNO-ESI can collaborate to translate insights into a (joint) actionable transformation plan.

3 Approach MBSE study phase 2

This second phase of the MBSE-study ran from 2022 to 2024. This phase consisted of one quick-scan session followed by four joint workshops aimed at identifying challenges, dilemmas, and attention points related to the key topics identified at the end of phase 1. In-between workshops, participants initiated deep-dive sessions in smaller settings to elaborate on specific details.

The agenda of the workshops was constructed in such a way that all participants could learn with and from each other and were “challenged” to translate insights into individual action plans. Each workshop consisted of multiple interactive elements:

- Conceptual framework: Introduction and scoping of the topic from a theoretical perspective.
- Seed presentation: An industry partner presents the topic from an industrial viewpoint.
- Guided group discussion: Deliberation on challenges, dilemmas, and key focus areas.
- Guest speaker: Insights from a speaker in a different application domain.
- Consolidation of key takeaways: Summarizing the main insights.
- Company-specific reflection: Translating key takeaways to each company’s context and planning next steps.

This report gives an overview of the observations and conclusions resulting from these workshops and deep dive sessions.

3.1 Phase2 Study Team

During the project, the composition of the study-team has been varying, most team members have been present during the whole study, while others joined later or left somewhere midway. Without explicitly making this distinction, the following people have been part of the study team (see Table 1):

Table 1 - MBSE Study Phase2 participants.

Alberto Fazzi	Philips	Jamie Mc Cormack	Thermo Fisher Scientific	Peter Nacken	Canon Production Printing
Atibha Behl	Philips	John van der Koijk	Philips	Pim Muilwijk	TNO
Alexandr Vasenev	TNO-ESI	Jonnro Erasmus	ASML	Rentia Barnard	ASML

Bas van der Leeuw	TNO-ESI	Joost Dierkse	Thermo Fisher Scientific	Richard Doornbos	TNO-ESI
Ben Pronk	TNO-ESI	Joris van den Aker	TNO-ESI	Rik Jansen	TNO
Clemens Raben	Thales	Jurriaan Luiken	Canon Production Printing	Roelof Hamberg	Canon Production Printing
Edwin Dorrestijn	Canon Production Printing	Krelis Blom	Philips	Ron Blom	Canon Production Printing
Erik Teesink	Philips	Maarten Bonnema	University of Twente	Sareh Heydari	Vanderlande Industries
Fatih Erkan	Philips	Marcel Verhoef	European Space Agency	Sannelie van der Westhuizen	Shell
Fatma Kiyici	Vanderlande Industries	Marcin Gramza	Thermo Fisher Scientific	Sander Kossen	TNO
Frank de Lange	ASML	Maria Jankovic	Philips	Sergey Libert	Vanderlande industries
Freek Molkenboer	TNO	Marjolein Velthuizen	Thales	Sezen Acur	TNO-ESI
Harald Keicher	Canon Production Printing	Maurice van der Beek	Philips	Teun Hendriks	TNO-ESI
Harry van de Velde	Shell	Maurice Stassen	Vanderlande Industries	Timon van Slooten	Thales
Henry Boonen	Philips	Patrick Vestjens	Canon Production Printing	Thomas le Montagner	Thales
Imge Gemci	Philips	Patrick Wender	Philips	Vlad Stefanovici	Thales
Jacco Wesselius	TNO-ESI	Paul Harvey	Philips	Wim de Jong	TNO
Jelena Marincic	TNO-ESI	Paul Schreinemakers	INCOSE NL	Wouter Tabingh Suermondt	TNO-ESI

TNO-ESI thanks these people and companies for their active contributions to the MBSE-study and to the conclusions and observations consolidated in this report.

4 MBSE and Models in Systems Engineering

4.1 Introduction

Systems Engineering is widely practiced in the high-tech equipment industry. To properly position MBSE within Systems Engineering in general, a working definition is needed. In a short exploration, preceding the first phase of the MBSE-study phase [2], TNO-ESI conducted a literature survey. Starting from a common definition of Systems Engineering, a working definition for MBSE was shaped [2]. These definitions and their rationale are elaborated once more in the sections below. This chapter concludes with a summary of the main findings of the first phase MBSE study [1] [3] to set the context for this following-on study report.

4.2 Systems Engineering

> "
> — *Definition:*
> *Systems Engineering is a* ***transdisciplinary*** *and* ***integrative*** *approach to enable the successful realization, use, and retirement of* ***engineered systems****, using* ***systems principles and concepts,*** *and scientific, technological, and management methods.*
>
> *We use the terms "engineering" and "engineered" in their* ***widest sense****: "the action of working artfully to bring something about". "****Engineered systems****" may be composed of any or all of people, products, services, information, processes, and natural elements.*

source: INCOSE [4]

Systems Engineering is an engineering discipline that has emerged from the space and defence industry. It focusses on the transdisciplinary, system-level approach to successfully realize, use, and retire systems. The INCOSE definition quoted above (taken from [4]) addresses the specific aspects of systems engineering in detail. Another, less detailed, description found in the SEBoK [5] of systems engineering emphasizes what it is all about:

A systems engineer helps ensure the elements of the system fit together to accomplish the objectives of the whole, and ultimately satisfy the needs of the customers and other stakeholders who will acquire and use the system.

The Systems Engineering Handbook of NASA [6], explains this in more detail:

Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. A "system" is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce system-level results. The results include system-level qualities, properties, characteristics, functions, behaviour, and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that

> *is, how they are interconnected. It is a way of looking at the "big picture" when making technical decisions. It is a way of achieving stakeholder functional, physical, and operational performance requirements in the intended use environment over the planned life of the systems. In other words, systems engineering is a logical way of thinking.*

The major difference between systems engineering and, e.g., software engineering and hardware engineering is that systems engineering addresses the interdisciplinary, system-level concerns. Starting from stakeholder concerns and a problem statement, it defines the system structures that cross the boundaries of engineering domains (including people, facilities, documents etc. as expressed in the definition of NASA as quoted above from [6]). Systems[2] engineering concentrates on the design and application of "the whole" as distinct from the parts.

At TNO-ESI we have expressed this as follows:

> ***Systems engineering is the interdisciplinary field of engineering and engineering management that concentrates on how to design and manage effective systems over their full life cycles.***

This definition emphasizes that systems engineering is not only about technical engineering aspects; it is also about *engineering management*: ensuring that all engineering is done to assure that system effectiveness is achieved in a controlled way. Effectiveness should not come "by coincidence," all processes should be in place to ensure that effectiveness will be achieved.

Systems Engineering in The Netherlands. In The Netherlands, Systems Engineering is practiced widely. The Netherlands has a strong presence in the high-tech equipment industry sector with world-wide renowned organizations. Innovations now take these systems (e.g., nanometre accurate lithography systems, angstrom resolution electron microscopes, minimally invasive medical equipment, commercial printing equipment and advanced warehousing systems) towards unprecedented levels of features and functions, increasing complexity every day.

Consequently, R&D organizations have grown, with (business-) critical issues needing to be addressed in eco-systems of partners (e.g., supply chain partners, field service partners, innovation partners). Many R&D employees are employed for a lengthy period, sometimes they work their whole professional career at a single company. They have in-depth knowledge about the current developments as well as the installed base. Although this knowledge is essential, keeping it up to date is expensive.

The technical and business complexity forces these industries to grow, which means an influx of new people — who do not have the full design history in their minds. Also, the retirement of senior employees, who are working on crucial expertise, is a source of loss of know-how. To maintain market position, a solution for retaining critical know-how is crucial. Above drivers, have driven this industry sector to have increasing interest in replacing their classical Systems Engineering approach by a (more) Model Based approach.

[2] It is worth noting that we talk about systems (plural) engineering and not about system (singular) engineering. The reason for using the plural form is that a system does never exist on its own. It is part of a context of systems, other systems are used to manufacture it, to support and service it, etc. This introduces all sorts of complexities to the systems engineering task, which are well explained in "the seven samurai"-paper of James Martin [34].

4.3 Model-Based Systems Engineering

Model-based systems engineering was kicked off by INCOSE by its MBSE Initiative in January 2007 [7]. INCOSE considers MBSE part of a long-term trend towards model-centric approaches throughout development and later life cycle phases [8]. Model-Based Systems Engineering (MBSE) is (in contrast to Document-Based Systems Engineering – DBSE) an approach to systems engineering based on the vision that using (domain) models for expressing, exchanging and analysing engineering information is a key enabler to enhance the effectiveness and efficiency of systems engineering. Instead of using a set of interlinked documents, models are used. These models are based on well-defined formalisms, and they form a consistent, authorative engineering truth.

When we combine this with our definition of Systems Engineering, we define Model-Based Systems Engineering at TNO-ESI as follows:

> ***Model-Based Systems Engineering*** *is the interdisciplinary field of engineering and engineering management that concentrates on* ***creating and exploiting models as primary means of information exchange, analysis, and simulation*** *to design and manage effective systems over their full life cycles.*

A general concept in MBSE is that the models are the authoritative[3] source of Systems Engineering information for everyone, throughout the full life cycle of a system. Those models are not add-ons to systems engineering documents. They are much more: in the ultimate MBSE-implementation, they would replace these documents. If documents are needed, they can be generated from the models, but in case of doubt the models are authoritative, they overrule the documents.

4.4 MBSE ≠ SE with Models

In the Dutch high-tech equipment industry, models abound, but they are not yet the authoritative source of information. Most SE related models have a single purpose and are disconnected. The sector looks to MBSE to improve their SE practice [9] [10] [11] [12].

During our discussions, one of the questions that was addressed was the following: doesn't every (systems) engineer use models? Aren't we all doing MBSE all the time, at least to some extent? In the study, we concluded that this question should be answered with a clear "no." It is important to emphasize that MBSE really wants systems engineering to take a new course. It is not just "engineers using models while systems engineering."

We have seen many cases where models were used by systems engineers. This is indeed a common and necessary practice. But in most cases, these models were disconnected, single-purpose models. The resulting models were copied into documents. In the end, these documents were the authoritative source of information, the deliverables per the prevailing development process. We noticed many occasions that documents, including the modelling results, became outdated and inconsistent. Screenshots of models are a dead representation of the model. In MBSE, the models are expected to be a living representation of all systems engineering information. In MBSE, models are connected rather than for a single purpose: the

[3] In previous versions we wrote that models are the *single* source of information. After the panel discussion during the IDEW'21 webinar on MBSE [2] we decided to use "authoritative" instead. The reason for this is that i) information can be available in other forms to, preferably derived from models, but that the models will always be authoritative in case of any doubt and ii) there doesn't have to be a single model, the information can be contained in multiple, diverse, connected and consistent models.

impact of changing one model will ripple through the connected models to indicate the consequences throughout the full system. In MBSE, the models are expected to be up-to-date and consistent. The MBSE-methods and tools aim to support the systems engineering community to achieve this.

This does not mean that MBSE and SE are unrelated. As the definitions already emphasize, MBSE is a particular way of doing SE. One cannot do MBSE if one is not capable of doing SE. This applies to an individual, just as well as to an organization. Before embarking on MBSE, first SE should be mastered. As sketched in Figure 1, successful introduction of Model-Based Systems Engineering builds upon previously established personal and organization competencies and processes: i) systems-thinking and ii) document-based systems engineering. Systems engineering includes requirements engineering. The first step into MBSE is typically to collect system requirements in a repository rather than in documents. In the figure, we have called that “model-based” requirements engineering.

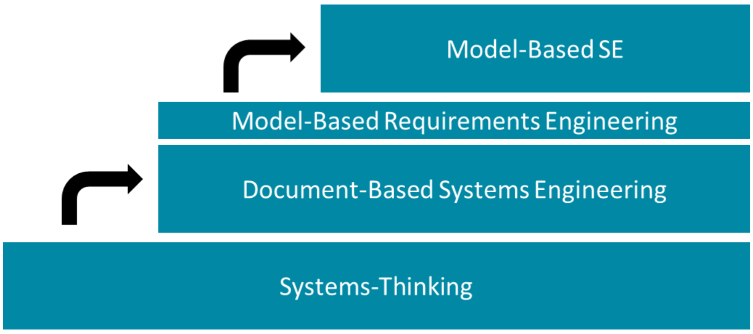

Figure 1 - MBSE builds on SE and Systems Thinking

4.5 MBSE in the Netherlands: Observations MBSE study phase 1

The observations of the phase 1 of the MBSE study are described in a public report [1] and summarized in an article [3]; a short summary is given here.

The integration of Model-Based Systems Engineering (MBSE) in the high-tech equipment industry reveals several critical needs and challenges. The high-tech equipment industry typically operates in a brownfield context, incrementally building on previous system generations rather than starting with fresh system concepts. Transitioning fully to MBSE is slow due to the effort required to convert legacy documentation into models. Capturing implicit design knowledge—often stored in the minds of experienced engineers—is essential to make models the "authoritative source of truth." MBSE must support the evolutionary delivery of systems while leveraging knowledge of past generations. Alse, the workforce may be changing faster than the lifetime of high-tech equipment, so carrying over information between generations of engineers is becoming very important.

MBSE often starts as a confined activity within systems engineering, focusing on system-level models for structuring requirements and allocating these to system components. To realize MBSE's potential, it must bridge gaps between systems engineering and other disciplines through bi-directional information flow. Interdisciplinary collaboration is crucial, requiring models that are understandable across various stakeholders and disciplines.

The high-tech equipment industry requires interoperable MBSE tools and methods that enable model-based collaboration across organizational and supply chain boundaries while addressing confidentiality concerns. The industry sector relies on platform-based approaches, emphasizing reusable building blocks and product line engineering. MBSE tools must support platform modelling, selection of components, and system synthesis to meet diverse customer needs. Interfaces and standards for multi-disciplinary components (software, mechanical, electrical, etc.) must be described formally to ensure compatibility.

Highly customer-specific configuration demands result in significant system diversity. MBSE must provide tools for managing diversity without overwhelming model complexity and for reasoning about both individual configurations and product families. Interface standards must be modelled effectively to avoid unnecessary system variants caused by technical incompatibilities.

Beyond functional requirements, MBSE must address system qualities (e.g., performance, reliability) using quantitative models. Simulation tools integrated into MBSE frameworks are critical for analysing and optimizing system configurations. The scope of MBSE should expand to include non-functional aspects like manufacturing, installation, and maintenance considerations.

The industry increasingly adopts agile and continuous integration/delivery methods, moving away from traditional waterfall approaches. MBSE must adapt to these methodologies without compromising agility, supporting concurrent engineering and iterative development at the system level. This requires low-threshold stakeholder access to, and involvement with the information contained in the MBSE models, without these stakeholders needing to learn nor understand MBSE notations or formalisms.

A structured transition path is essential for embedding MBSE into organizations, including developing necessary systems engineering competencies. The industry needs guidance on leveraging MBSE to unlock business value, particularly in navigating brownfield constraints and optimizing platform investments. MBSE offers promise as an authoritative and collaborative platform for systems engineering. However, its effective implementation in the high-tech equipment industry requires addressing diverse needs, from managing legacy systems and fostering collaboration to integrating with agile practices and enabling platform-based innovation.

4.6 Factors Influencing the Added Value of MBSE Introduction in the high-tech sector

In the MBSE study phase 1, the relevant factors influencing the added value of MBSE introduction have been identified, see also the article in INCOSE INSIGHT magazine [3]. MBSE has been first applied in Aerospace and Defence in long-running “engineer-to-order” type projects. From then on, other domains have adopted or experimented with MBSE.

To support the High-Tech Equipment Industry in introducing MBSE, the influencing factors need to be understood that drive the added value for MBSE over “just” doing Systems Engineering. In phase 1 these factors were identified in part from success reports of application of MBSE in various domains and complemented with insight in the nature and strengths of MBSE methods and tools, and specifically the Requirements-Functional-Logical-Physical (RFLP) approach. Figure 2 presents an overview of these (generic) influencing factors.

As shown in Figure 2 (on the left), the nature of the systems may have a considerable influence on whether MBSE could add significant value. MBSE thrives when the design challenge is in balancing and decomposing multi-disciplinary physics (hence the underlined Physical). When cyber aspects (IT, data, or cloud), or management of emergent behaviour dominates complexity, then MBSE is less suitable to manage the complexity of such aspects.

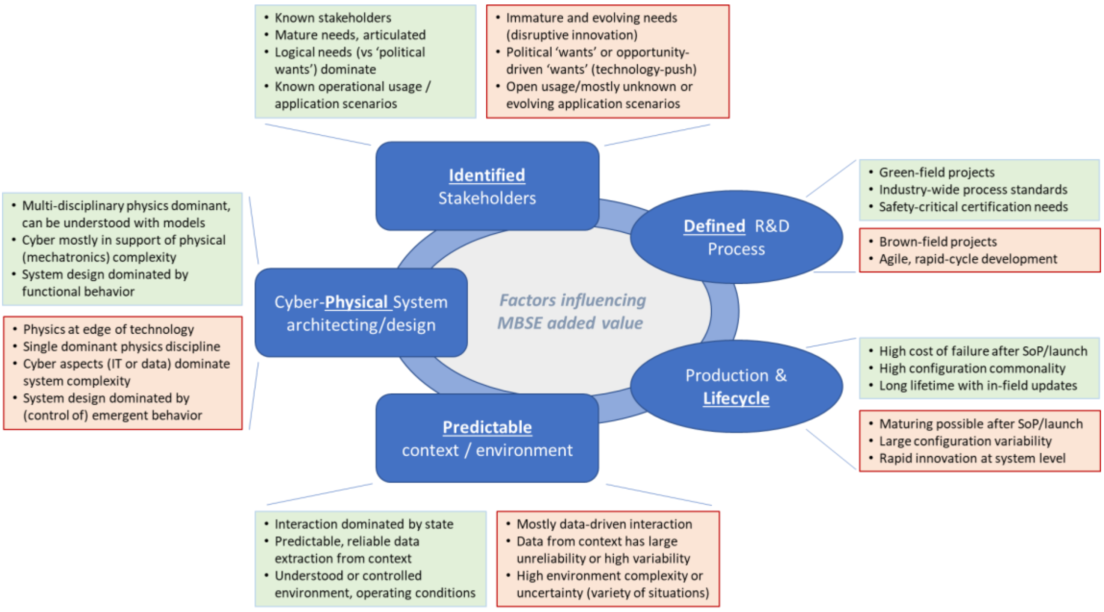

Figure 2 - Factors influencing the added value of MBSE (positive factors in green, negative factors in red).

Stakeholders should be known and able to articulate their needs (hence the underlined Identified in Figure 2). MBSE needs well-articulated system requirements, which form the basis of traceability into the design and verification of its decomposition and properties.

A system's context (Figure 2 bottom) should be understood, to be captured in models (hence the underlined Predictable). When this context sees large uncertainty or sees mostly data-driven interaction, then this presents difficulties for (typically function-oriented) MBSE approaches. Specialized model or data-driven approaches are then called for (e.g., capturing driving scenarios in automated driving for in-lab replay tests rather than the 'standard 'RFLP' approach).

With respect to the R&D process (Figure 2, right and top), green-field projects allow complete use of MBSE over the full design scope (emphasized by the underlined Defined). In contrast, brown-field development for incremental design upgrades faces missing models and lost know-how. Recreating these for MBSE, incurs high R&D overhead and long time-to-value.

Finally, with respect to Production and Lifecycle (Figure 2, right and bottom), MBSE is particularly suited to minimize unacceptable risks when a high cost of failure could occur after Start-of-Production (SoP) (indicated by the underlined Lifecycle) as is typically the case with safety-critical systems, e.g., road vehicles or commercial aircraft. For products that can be launched quickly as a minimally viable product, MBSE overhead may be too much.

Most MBSE methods and tools implement a variant of the Requirements-Functional-Logical-Physical (RFLP) approach. This approach has been particularly well suited for certain domains and organizations. Figure 2 provides contrasting factors to consider where MBSE could add significant value, or where the value could be less or not significant at all over "just" doing Systems Engineering with (disconnected) models.

5 Phase 2 MBSE needs & Interests high-tech equipment industry

5.1 Introduction

The MBSE study phase 1 of ESI and partners [1] identified basic needs and interests of the High-Tech Equipment Industry with respect to the capabilities and strategies of contemporary MBSE-methods and tools.

During this phase 1 of the study, several more generic observations and attention points were identified. Firstly, modelling is a key aspect of design exploration and analysis. This needs strong interfaces between simulation and analysis tools and the MBSE-core tools to assure consistency, cohesion, and authoritativeness to support the collaboration and concurrent engineering. Secondly, if the models become the authoritative source of systems engineering information, then they should capture design rationale and intent (today, architects spend a lot of their time talking with design teams to convey these). Thirdly, MBSE methods and tools are needed to create models from legacy design artefacts (e.g., documents, Excel sheets, Visio diagrams, CAD files) in a brown-field environment. Lastly, given the sector's MBSE motivations, integrating key aspects of platform-thinking and product line engineering into the MBSE-core methods and tools is needed for MBSE to be effective in this sector, including reasoning about system variants/diversity and across legacy.

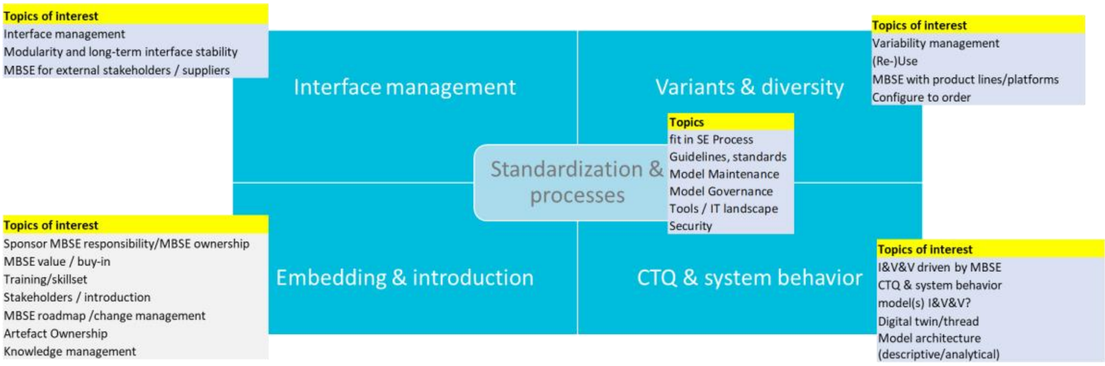

Figure 3 - 4+1 interconnected cluster topics as main themes for phase 2 workshops.

5.2 MBSE study topics phase 2

To deepen the results of phase 1 of the MBSE study, an agenda-setting workshop was organized to identify key topics for further study. In this agenda-setting workshop, the European Space Agency (ESA) was invited to give an external perspective on MBSE and the introduction of MBSE (see also section 9.2). This agenda-setting workshop led to the following four cluster topics, each addressed in follow-up deep-dive workshops:

- Interface Management and MBSE
- Variants & Diversity and MBSE
- Critical to Quality (CTQ) & System Behaviour
- Embedding and Introduction of MBSE

These four cluster topics and related subtopics (see also Figure 3) are further introduced in the next sections.

5.2.1 Interface management and MBSE

Effective interface management is crucial for ensuring seamless interaction between system components, which helps reduce the risk of late integration problems and costly redesigns. Therefore, improving interface management has a large value, even more for organizations with geographically distributed development locations. The following were the expressed points of interest for knowledge sharing on interface management and MBSE:

- **Interface Management as a Starting Point for MBSE**: Organizations need a clear structure for how various parts of the system communicate and integrate. MBSE is anticipated to provide a systematic framework for defining and managing interfaces, enhancing traceability and consistency throughout the system's lifecycle. Immediate value can be created from the first interface onwards being modelled with MBSE.
- **Modularity and Long-Term Interface Stabilit**y: Maintaining stable interfaces over time is essential, especially as individual modules are updated or replaced in the evolutionary design approach of the sector. MBSE is anticipated to support long-term interface stability by facilitating modular designs, ensuring interfaces remain consistent and fit-for-purpose over time.
- **Application of MBSE for External Stakeholders and Suppliers**: Collaboration with external stakeholders and suppliers necessitates a clear framework for communication and precise specification of interfaces. MBSE is anticipated to enhance this collaboration by offering a comprehensive model-based framework for consistent and complete interface specifications, improving the effectiveness of interactions with external partners.

5.2.2 Variants & Diversity and MBSE

Effective management of variants and diversity is essential for the high-tech equipment industry to remain competitive in today's market. Product line engineering, which involves building systems out of standard building blocks, is a widespread practice in the industry. Organizations face the complexity of an increasing number of product variations, while needing to ensure that they meet diverse customer needs, and at the same time optimizing R&D, manufacturing, and maintenance efforts. Therefore, improving the management of variants and diversity has significant value. The following points highlight the expressed interest in knowledge sharing on variants and diversity in the context of MBSE:

- **Variability management and reuse**: Organizations face the challenge of managing a wide range of system configurations and variants, which can be complex and resource intensive. MBSE is anticipated to provide a structured approach for managing these variations. By using models as the authoritative source of information, it is hoped that organizations can more easily manage and track system variations, enhancing the reuse of components and designs. This approach aims to reduce the need for extensive rework and facilitate the identification of commonalities and differences between variants.

- **MBSE with product lines and platforms**: Managing product lines and platforms involves defining and coordinating the relationships between various products and their components, which can be challenging. MBSE is seen as particularly promising in this area, as it provides a framework for representing the entire product line, including common components and variations. This approach is expected to improve coordination and integration across the product line, ensuring consistent and efficient development.
- **MBSE and configure-to-order strategies**: Organizations often need to manage system configurations and variations based on specific customer requirements, which can be complex and time-consuming. MBSE is anticipated to enhance configure-to-order strategies by providing a structured approach to managing these configurations. By using models as the authoritative source of information, it is hoped that organizations can more easily define and manage different configurations, enabling more efficient and effective customization.

5.2.3 Critical to Quality (CTQ) & System Behaviour and MBSE

Effective management of Critical-to-Quality (CTQ) properties and system behaviour is essential for ensuring high-tech systems meet customer expectations and contractual agreements. As product complexity increases, managing CTQ properties throughout the development process becomes challenging and risks difficult to mitigate. However, successfully addressing these challenges provides a competitive advantage, leading to a stronger market position. The following points highlight the expressed interest in knowledge sharing on Critical-to-Quality (CTQ) and System Behaviour in the context of MBSE:

- **IVVQ driven by MBSE:** There is a need for a structured approach to Integration, Verification, Validation, and Qualification (IVVQ) to ensure all requirements are accurately captured and traced. MBSE is anticipated to improve this process by using models as the authoritative source of information, allowing for better verification and validation before physical prototypes are built.
- **Simulation and Testing:** Identifying potential issues early in the development process is crucial to reduce the risk of costly redesigns and delays. MBSE is anticipated to facilitate this by using models to simulate and test different scenarios, supporting 'model-in-the-loop' testing, and ensuring all requirements are met.
- **Model Architecture**[4]**:** A well-defined model architecture or model-of-models architecture is needed to accurately capture and trace system requirements and behaviours and sustain lifecycle changes. MBSE is anticipated to support this by providing structured methodologies for defining and managing model architectures, linking models in e.g. federated model architectures, so enabling better verification and validation through simulation and testing.
- **Model Management:** Consistent and reliable models are essential throughout the system's lifecycle to ensure accurate representation of requirements and behaviours. MBSE is anticipated to provide guidelines for creating, updating, curating, validating, and maintaining models in the engineering lifecycle process.

[4] A model architecture in MBSE refers to the structured organization of the various model elements, views, relationships and interfaces used to represent a system's design in a possibly heterogeneous modelling environment.

5.2.4 Embedding and Introduction of MBSE

MBSE is recognized as beneficial for managing the increasing complexity of high-tech systems by enhancing collaboration, improving traceability, and facilitating better decision-making throughout the system lifecycle. As companies strive to improve their development processes and ensure product quality, the transition from traditional document-based approaches to model-based methodologies presents both challenges and opportunities. The following points highlight the expressed interest in knowledge sharing on the introduction and embedding of MBSE in organizations:

- **Sponsor MBSE responsibility/MBSE ownership:** Successful implementation of MBSE requires strong sponsorship and ownership within the organization. Senior leaders must champion MBSE initiatives, providing the necessary resources and support to ensure their success. Establishing clear roles and responsibilities for MBSE ensures that all stakeholders are aligned and committed to the initiative. The question is how to ensure continuous leadership support for MBSE initiatives?
- **MBSE value/buy-in:** Achieving buy-in for MBSE is crucial for its successful implementation. Organizations must clearly articulate the value of MBSE, demonstrating how it can improve system development processes and outcomes. Highlighting the benefits of using models as the authoritative source of information is essential to gain the support and commitment of all stakeholders. The question is how best to articulate value, and what are the good examples of MBSE's value that can be shared with stakeholders?
- **Training/skillset:** Effective implementation of MBSE requires a skilled workforce with the necessary training and expertise, including SE expertise and experience. Organizations must invest in training programs to ensure that their employees have the knowledge and skills required to use MBSE tools and methodologies effectively. The question is what training programs and resources are most effective for developing MBSE skills and sustaining MBSE practice?
- **Stakeholders/introduction:** Introducing MBSE requires careful planning and coordination with all stakeholders. Organizations must engage stakeholders early in the process, ensuring that they understand the benefits, implications, and limitations of MBSE. This includes clear communication and education about MBSE, addressing any concerns or resistance, and fostering a collaborative approach to implementation. The question is how can stakeholders be involved best, and concerns and resistance to MBSE be addressed?
- **MBSE roadmap/change management:** Developing a clear roadmap for MBSE implementation is crucial for its success. Organizations must outline the steps and milestones required to achieve their MBSE goals, providing a structured approach to change management. By providing a clear roadmap, organizations can achieve the desired benefits, by effectively integrating MBSE into their systems engineering practices. The question is what are the key milestones and activities in an effective MBSE roadmap?
- **Artefact ownership:** Effective implementation of MBSE requires clear ownership of artefacts, ensuring they remain consistent and reliable throughout the system's lifecycle. Organizations must establish roles, responsibilities, and guidelines for creating, updating, and maintaining artefacts, ensuring they accurately represent the system's requirements and behaviours. The question is how can organizations maintain the consistency and reliability of MBSE artefacts?
- **Knowledge management:** Knowledge management is crucial for the successful implementation of MBSE, as it ensures that critical know-how is retained and accessible to all stakeholders. Organizations must establish clear guidelines for capturing, storing, and

sharing knowledge, ensuring it remains consistent and reliable throughout the system's lifecycle. The question is what methodologies and tools are most effective for MBSE knowledge management?

6 Workshop 1: Interface management and MBSE

6.1 Introduction

The transition from a document-based organization to a model-based organization is a paradigm shift for many organizations. Organizations must find new ways to deal with tools, languages, models, abstractions, and development processes. This makes many organizations hesitant to implement MBSE, due to high cost and considerable risk of failure. They need some kind of introductory roadmap where small steps can be made with moderate cost and immediate value.

Introducing MBSE by explicitly focusing on interfaces is such a pragmatic approach. During System Integration, when all the designed parts come together, most issues occur at the interfaces. The organization must fix them, sometimes requiring costly and time-consuming redesigns. So, the Return on Investment for MBSE is already positive when just a few of these interface related integration issues can be avoided.

Interface management provides a practical first step toward achieving control over distributed teams and development efforts. Its primary advantage lies in its simplicity: you can begin with a single, critical interface without requiring a complete system model. Managing interfaces is essential for handling diversity, fostering innovation, and mitigating integration problems.

In this section, we look at strategies and aspects for using MBSE to manage interfaces. First a conceptual framework is presented, then the workshop questions and challenges are discussed, and finally the conclusion and outcomes of the MBSE phase 2 workshop 1 with this topic are described.

6.2 Conceptual Framework

To introduce the topic TNO-ESI presented a conceptual framework addressing some key concepts on interface management (see also [13] [14]). This framework addresses the concept of interfaces, relationships between components and interfaces, classification of interfaces, and governance of interoperability. These topics are briefly discussed in the next sections.

6.2.1 What is an interface?

There is a broad consensus on interface definitions, their specifications, and their use. From the literature we can find several interface definitions which all point in the same direction.

- Wheatcraft [15] defines it as “An interface is a boundary where, or across which, two or more parts interact.”
- NASA [16] defines it as “An interface is that design feature of a piece of equipment that affects or is affected by a design feature of another system.”

- Wiki [17]: “An interface is a shared boundary across which two or more separate components of a (computer) system exchange information.”
- Davies [18]: “A shared boundary between two (or more) Systems or System Elements, defined by characteristics pertaining to functional or physical exchanges between them.”

Figure 4 provides a closer look at the essence of an interface. The interface is represented as an observation plane between two components CP1 and CP2 where the interaction manifests.

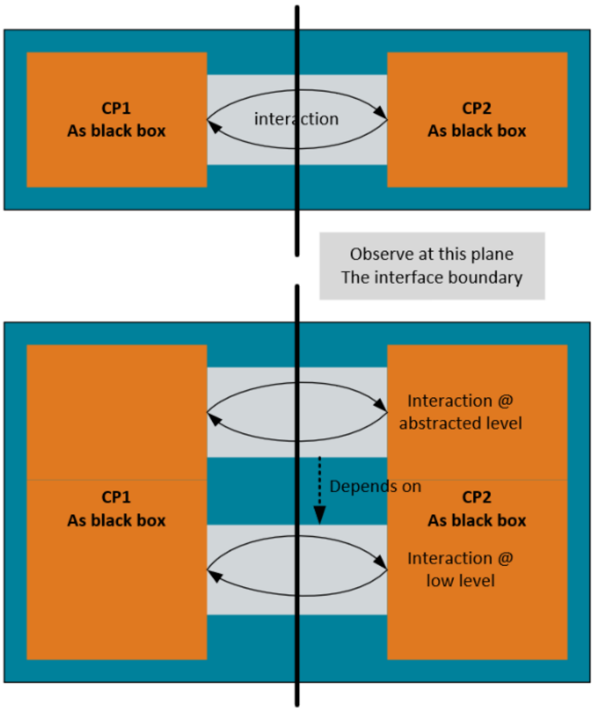

Figure 4 - The essence of an interface.

These interactions are represented by Figure 4, top image, where the interaction of components CP1 and CP2 is presented at the cutting boundary. Interactions can be decomposed where a lower-level type of interaction supports a higher, more complex interaction as presented by Figure 4, bottom image.

Most definitions describe an interface as a surface plane (German: “Schnittstelle”) where interactions between components CP1 and CP2 occur, such as the exchange of mass, energy, or information. Interfaces focus on interactions rather than the components themselves, allowing systems to be viewed as sets of interacting black boxes, which is beneficial for MBSE. Describing interactions at a meaningful level of abstraction is crucial; for instance, engineers typically avoid atomic-level details and focus on their specific disciplines. Davis suggests that interactions can be layered, with higher abstraction layers depending on lower ones, similar to communication protocol stacks. Fluid and electrical interfaces exemplify this, where higher-level abstractions are based on underlying physical principles.

6.2.2 Components and their interfaces

Components and interfaces are fundamental concepts in systems and also software engineering. Components and interfaces are closely related as they play key roles in defining the structure and observable interactions within a system. Interfaces define the boundaries and communication protocols between components, enabling a modular and well-organized system design.

There is a wide consensus how to describe components and their interfaces. For example Davis [18], Wheatcraft [19] de Weck [15], the NASA [16] all point into the same direction. In addition, many modelling languages and tools support the same approach: SysML [20], Modelica [21], ComMA [22]. These concepts are straight forward and presented by Figure 5.

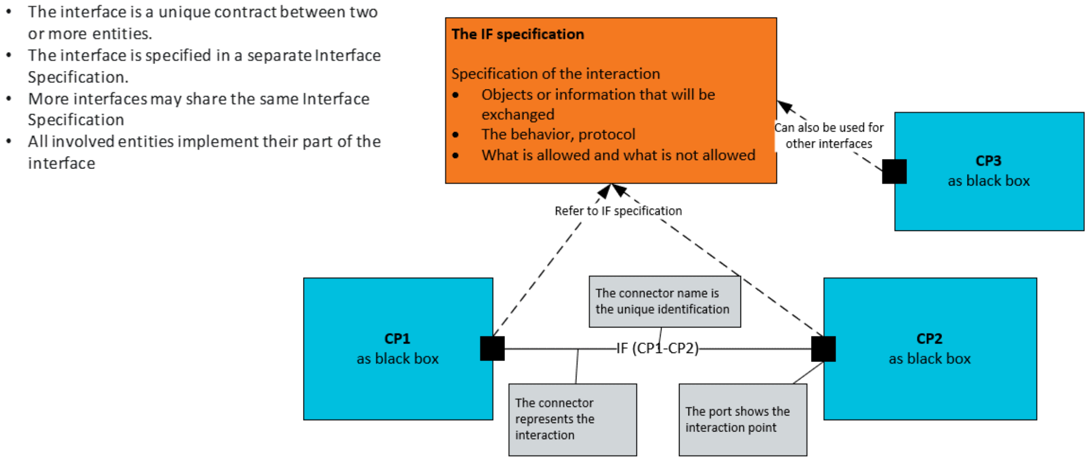

Figure 5 - Concepts of components and their interfaces.

Consider two components CP1 and CP2 who share a common interface (IF). Such an interface concept requires two aspects that come together: The Interface Specification (IFS) and the actual implementation. In more document-focused organization, the IFS is usually called Interface Control Document (ICD).

The Interface Specification (IFS) defines the interaction between components. If both implementations refer to the same IFS and consider complementary aspects, interoperability is assumed. The IFS includes the elements of the interaction and its behaviour over time. Multiple specifications can form a layered IFS, avoiding the need for a monolithic specification. For example, in communication interfaces, electrical and frame transfer specifications can be reused across different protocols, allowing IC vendors to use the same chips for various applications.

Implementations are represented by ports, where relevant features are exposed. The connector IF (CP1-CP2) links both ports, each of which may differ in implementation. For instance, household electrical sockets and plugs have different mechanical implementations but comply with the same electrical IFS. In communication protocols, software implementations can be independent but interoperable if based on the same IFS (e.g., TCP/IP standards).

Each interface and IFS must have a unique identification. In cases where both ends of the interface refer to different but compatible IFS, interoperability is maintained, such as with backward-compatible communication protocol versions.

Thus, the important Interface Principles are the following:

- Each IF and IFS must have a unique identification.
- The IF can be represented as connected ports.
- Implementations on both sides may differ.

- Interoperability requires compliance with the same or compatible IFS.

6.2.3 Classification of interfaces

A typical system may contain thousands of interfaces. To keep an overview, these interfaces may need to be organized or grouped into classes or categories of similar interfaces. Similar sets of interfaces may be specified and treated in the same way. It also acts as a checklist to see if no relevant interfaces are missing. There are many ways to structure a random set of interfaces. This section discusses some ways to structure interfaces.

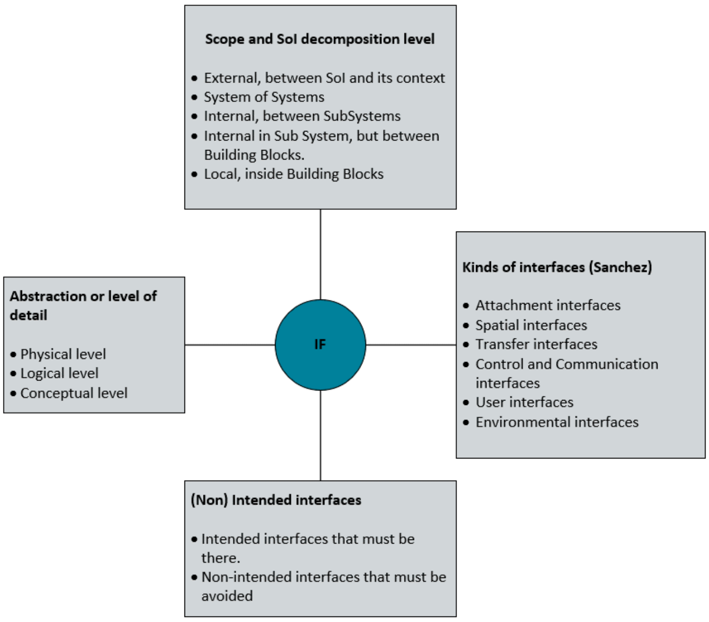

Figure 6 - Interfaces can be structured into different classification schemes.

Four examples of a classification are presented by Figure 6. The interfaces classes in the figure are the following:

- The various kinds of interfaces. Sanchez [23] proposes structuring of interfaces by their purpose and function. Attachment interfaces are different from communication interfaces.
- The scope of the interface with respect to its system. We can arrange interfaces according to their scope with respect to the System of Interest (SoI). A typical system could be decomposed into sub-systems and further into building blocks. Consequently, we can also identify interfaces at these levels.
- The abstraction level of the interface. This is particularly useful in combination with modelling in the context of MBSE. The right level of abstraction also holds for the interfaces.
- The intention of the interface. Not all interfaces are desired and designed. There is also a set of interfaces that emerge from the design and needs to be mitigated or suppressed. Sometimes the design needs to be made resilient. Some examples are various kinds of cross talk and interference on physics aspects, e.g. acoustic noise, vibration, light, electromagnetic radio signals. The performance of high-tech equipment that works with

nanometre precision (e.g. lithography scanners or electron microscopes) is for a substantial part based on the elimination of such cross talks.

6.2.4 Interoperability requires interface governance

Interface standardization and governance are essential for ensuring that different components, systems, or services can effectively work together. In many cases the system is structured according to Conway's law [24]: technical interfaces also cross organizational boundaries.

A typical pattern, often found in industry, is where a design team changes a component due to new technical requirements and consequently has to change some of the interfaces. If this is a breaking change, the owners of all interacting components have rework as well. Sometimes, this rework is unforeseen and not budgeted in product development. In an even worse scenario, it might result in a cascade of interface changes. This results not only in additional cost and lead time of product development, but also in additional configurations that must be maintained and serviced. Keeping interfaces stable and reducing interface changes to a minimum is a highly effective approach. It can save a substantial amount of valuable development resources in terms of time, engineers, test facilities and product variations, spare parts.

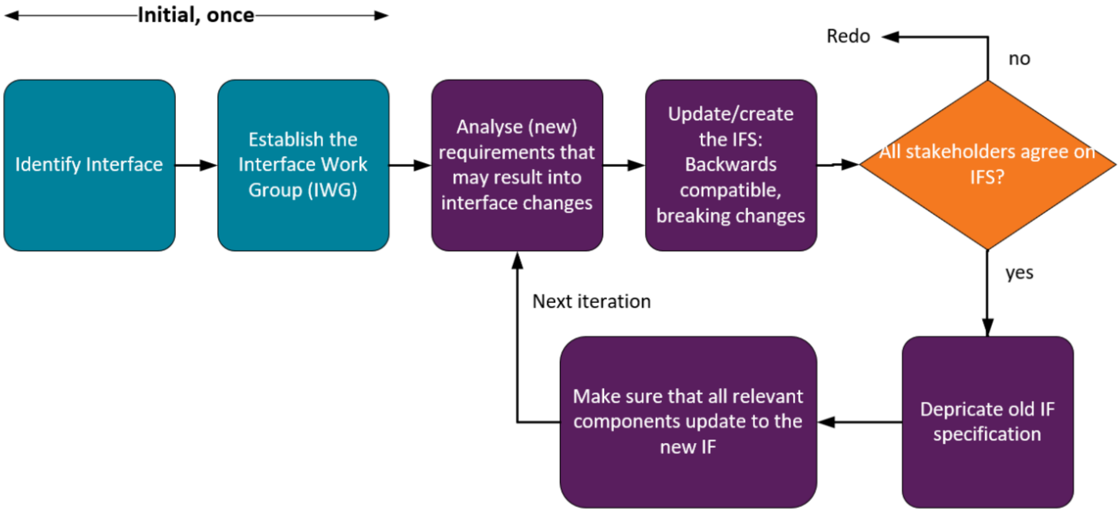

Figure 7 - A simplified governance process.

If the IFS is an external standard, governance and stability are usually already in place. However, when the industry defines its own internal interfaces and IFS, they are often not explicitly governed, although many stakeholders of various parts of the organization are involved. This can be repaired by introducing a simple governance process on the IFS, as depicted by Figure 7. Since stakeholders usually have conflicting concerns, the process should establish the best possible compromise. The interfaces and its related IFS should have an owner who brings the stakeholders together. The most important step is agreement by all stakeholders on the proposed specification. In the figure, this step is presented by the orange diamond.

6.2.5 Why MBSE for interface-management?

Introducing MBSE by focusing on interfaces is a low-risk, cost-effective approach. Integration issues often emerge at the interfaces during system assembly, leading to expensive redesigns. By preventing these issues, the return on investment becomes evident early.

Interfaces span boundaries across system components, project teams, engineering disciplines, and subcontractors. An interface-centric MBSE approach empowers system architects to maintain control of the overall design, ensuring system-wide consistency. These models generate essential artifacts, enable analysis, and support governance while providing clarity at the system level.

Companies sometimes struggle with the introduction of MBSE in their organization because the investments are relatively high, while the benefits in the short term are unclear. Michael Ali [25] emphasizes that starting with interfaces is a pragmatic way to introduce MBSE in legacy situations. By focusing on the interfaces, one can consider the System of Interest as a set of communicating black boxes. This already dramatically reduces the complexity of the system reasoning.

Both Davies [18] and Ali [25] mention that many integration issues are related to the component's interfaces. Davis emphasizes that when an organization does not actively manage interfaces, their number may scale quadratic with the growth of the number of its components (any component could end up interfacing with all other components). However, when the interfaces are properly managed, a rule of thumb is that the growth can be reduced up to a factor 2.

6.3 Questions and Challenges Discussed with Industry

Interface management plays a pivotal role in ensuring the efficiency and effectiveness of systems engineering and product development, the more so the organisation is more complex and more distributed. By identifying, defining, controlling, and verifying interfaces early in the development process, organizations can significantly reduce integration risks and avoid costly redesigns. A proactive approach supports the maintenance of modular platform architectures and enables a shift-left strategy—addressing interface issues during system architecture rather than during physical integration.

6.3.1 Objectives and motivation for interface-centric MBSE

The introduction of MBSE offers a structured and scalable way to formalize interface management. Through model-based representations, interfaces can be consistently defined, analysed, and governed across disciplines and organizational boundaries. This not only improves stakeholder communication by making interface requirements and constraints explicit but also supports the creation of digital twins at the interface level. These digital representations enable early validation of system configurations and facilitate standardization across product lines.

A key objective of interface-centric MBSE is to establish a governance process that ensures controlled evolution of interfaces. This includes maintaining an inventory of all system interfaces, creating standardized representations using MBSE tooling, and generating Interface Control Documents (ICDs) directly from models. Such practices can drive V&V of each interface, help prevent unnecessary divergence, and support long-term maintainability of system architectures.

By focusing on interfaces as a starting point, (SE-capable) organizations can achieve immediate value from MBSE without requiring a full system model. This pragmatic approach enables teams to build confidence, demonstrate early success, and lay the groundwork for broader MBSE adoption across the product lifecycle.

This section summarizes the key motivations for focusing MBSE efforts on interface modelling, as discussed by stakeholders across the high-tech equipment industry.

- **Low-risk, high-impact entry point.** Introducing MBSE through interface modelling allows organizations to start small, focusing on high-value areas like integration points, where issues are most likely to arise. This approach minimizes upfront investment while delivering tangible benefits early in the process.

- **System-wide consistency and control.** Interfaces span across components, teams, disciplines, and suppliers. MBSE enables system architects to maintain oversight and coherence across these boundaries, ensuring that design decisions remain aligned throughout the development lifecycle.
- **Artifact generation and governance support.** Interface-centric MBSE models can be used to generate specifications, support analysis, and formalize governance processes. This helps organizations manage interface evolution and maintain traceability across versions and stakeholders.
- **Simplification through abstraction.** Modelling systems as interacting black boxes reduces complexity and facilitates reasoning, especially in legacy environments. This abstraction supports clearer communication and decision-making across disciplines.
- **Scalability and modularity.** MBSE supports modular design and long-term interface stability, which is essential for evolutionary development and distributed teams. Stable interfaces allow components to evolve independently while maintaining system integrity.
- **Supplier collaboration and contract management.** Well-defined interface models improve communication with external stakeholders and suppliers, serving as contractual artifacts and reducing ambiguity. This strengthens collaboration and reduces integration risks across organizational boundaries.
- **Mitigating interface proliferation.** Poorly managed interfaces can scale quadratically with system complexity. MBSE helps contain this growth through structured modelling **and governance, reducing the number of variants and associated maintenance costs.**

These insights underscore the strategic value of using MBSE to manage interfaces, particularly in complex, multi-disciplinary environments. By focusing on interfaces, organizations can gain early wins and build momentum for broader MBSE adoption.

6.3.2 Challenges for Interface-Centric MBSE – Industry Perspectives

Building on the motivations outlined above, this section captures the key challenges identified by industry stakeholders for implementing interface-centric MBSE. The points are grouped into technical, governance, and organizational themes to reflect the multi-faceted nature of the transition.

6.3.2.1 Technical Challenges

In the workshop discussions, participants emphasized that the successful deployment of interface-centric MBSE hinges on addressing a set of foundational technical challenges. These challenges are particularly relevant in the high-tech equipment industry, where systems are complex, multi-disciplinary, and often developed in brownfield contexts. Establishing a consistent and scalable technical framework for interface modelling is essential to ensure traceability, reuse, and system-wide coherence. The following observations reflect the industry's need for structured approaches to inventory, standardization, and automation in interface management.

Key discussion points and challenges were the following:

- **Inventory and standardization.** Organizations need to systematically identify all interfaces in their systems and represent them consistently using MBSE tooling. This creates a foundation for traceability, reuse, and impact analysis.
- **Interface libraries and reuse.** Developing reusable interface libraries enables modularity and reduces duplication. These libraries can serve as reference points for future projects and support standardization across product lines.
- **Digital Twin development.** Building interface-level Digital Twins allows organizations to simulate and validate system configurations before physical integration. This supports early detection of incompatibilities and facilitates design space exploration.
- **Automated documentation.** MBSE tools should support automatic generation of Interface Control Documents (ICDs) and other artifacts. This reduces manual effort and ensures consistency between models and documentation.

By establishing a shared understanding of interface definitions and classifications, organizations can lay the groundwork for scalable MBSE deployment. This foundational clarity supports modularity, traceability, and reuse, while also enabling governance mechanisms that ensure interfaces evolve in a controlled and predictable manner.

6.3.2.2 Governance and Architecture Challenges

Governance and architectural alignment are critical enablers for the successful deployment of interface-centric MBSE. During the workshops, participants emphasized that without clear ownership, structured change control, and cross-disciplinary coordination, even well-defined interface models risk becoming obsolete or misaligned. As systems evolve and teams operate in agile and distributed settings, maintaining architectural coherence and managing interface evolution becomes increasingly complex.

Key discussion points and challenges were the following:

- **Ownership and accountability.** Clear responsibilities must be defined for interface specification and maintenance at both system and subsystem levels. This ensures that changes are carefully reviewed and approved.
- **Interface evolution control.** A governance process is needed to manage interface changes and prevent unnecessary divergence. This includes baselining specifications and coordinating updates across teams and suppliers.
- **Cross-disciplinary coordination.** Aligning hardware and software teams is essential, especially when dealing with agile development cycles and breaking changes. MBSE can help bridge these disciplines through shared models and structured communication.

- **Managing abstraction layers.** Interfaces must be defined at appropriate levels of abstraction to support both system-level reasoning and detailed implementation. This requires careful modelling and alignment with stakeholder needs.

Establishing governance mechanisms for interface evolution, ownership, and abstraction management is essential to maintain system integrity over time. These mechanisms must be lightweight yet robust enough to support agile development and cross-functional collaboration.

6.3.2.3 Organisational and Strategic Considerations

Beyond technical and architectural concerns, the adoption of interface-centric MBSE also raises important organizational and strategic considerations. Workshop participants highlighted that interfaces are not only technical constructs but also organizational boundaries that shape collaboration, innovation, and accountability.

Key discussion points and considerations were the following:

- **Bounded contexts for innovation.** Interfaces can be used to define clear scopes for teams and projects, enabling focused innovation and reducing ambiguity. This supports modular development and parallel engineering efforts.
- **Portfolio optimization.** Interface models help architects make informed decisions about platform composition and product variants. This supports strategic alignment and cost-effective reuse.
- **Stakeholder alignment.** Treating interface specifications as contracts with suppliers requires transparency and shared understanding. MBSE supports this by formalizing specifications and enabling traceable communication.
- Reverse Conway's Law. MBSE can expose organizational inefficiencies and guide structural changes that support system architecture. By modelling interfaces explicitly, organizations can align their organizational structure with their technical goals.
- **Communication and sustained commitment.** These objectives and challenges reflect the multifaceted nature of implementing interface-centric MBSE. Addressing them requires not only technical solutions but also organizational alignment, communication, and sustained commitment across the development lifecycle.

By treating interface specifications as formal contracts and using them to define bounded contexts, organizations can foster clearer communication, reduce ambiguity, and support modular development. Moreover, MBSE can help expose organizational inefficiencies, offering a pathway to reverse Conway's Law and realign structure with system architecture. Realizing these benefits, however, requires sustained commitment, cross-functional engagement, and a clear strategic vision.

6.4 Workshop Observations and Conclusions

The high-tech equipment industry is characterized by complex, low(er) volume systems, which are typically developed in distributed environments in brownfield environments. In this context, the workshop on interface-centric MBSE revealed that modelling interfaces is not only a technical necessity but also a strategic enabler. Participants shared practical insights into how interface modelling supports modularity, supplier collaboration, and system integration, while also exposing organizational inefficiencies and guiding structural improvements. The observations in this section reflect the industry's collective experience and highlight the pragmatic value of starting MBSE adoption through interface management—offering quick wins and laying the foundation for a broader transformation.

6.4.1 Workshop Observations

The workshop on interface-centric MBSE revealed a shared understanding among participants that modelling interfaces offers a practical and impactful entry point for MBSE deployment, particularly in brownfield environments. The following observations summarize key themes that emerged during the workshop discussions.

- **Interfaces as control points in distributed development.** Participants emphasized that modelling interfaces provides immediate leverage in managing distributed development efforts. By formalizing interactions between components, teams can clarify responsibilities and reduce ambiguity in cross-functional collaboration. This is particularly valuable when collaborating with external suppliers, where interface models can serve as contractual artifacts. The ability to visualize system interactions early helps mitigate integration risks and supports smoother system assembly. Several participants noted that modularity is essential for enabling innovation, and that interface models can help structure development efforts across sites.
- **Classification and governance as enablers of modularity.** A recurring theme was the importance of clearly defining and classifying interfaces to support modularity and interoperability. Interfaces function as natural boundaries for assigning team ownership, especially in geographically distributed organizations. Classification schemes help teams maintain consistency across system boundaries and act as checklists to ensure completeness. Governance mechanisms as essential to control interface evolution, prevent unnecessary divergence, and maintain traceability. Participants noted that without governance, interface changes can cascade across systems, leading to costly rework and variant proliferation: hence an emphasized importance of defining scope per project and ensuring alignment between functional chains and interface ownership.
- **Phased MBSE introduction through “Share, Secure, Automate”** stages. To manage complexity and organizational readiness, participants proposed a phased approach to MBSE deployment. The “Share” phase focuses on improving communication and reducing ambiguity through interface visibility. The “Secure” phase emphasizes analysis and maintainability, ensuring that decisions and rationale are preserved. Finally, the “Automate” phase targets the generation of documentation and models, reducing manual effort and increasing consistency. This stepwise strategy was seen as a way to build confidence and demonstrate value incrementally (in general for introduction of MBSE).
- Organizational alignment and Conway’s Law considerations. Participants discussed how MBSE can help expose organizational inefficiencies, particularly those described by Conway’s Law, which postulates that system architectures mirror communication structures. Interface modelling was seen as a way to make these inefficiencies visible and guide structural improvements. However, MBSE should not be introduced in isolation. Foundational Systems Engineering capabilities and reference architectures must be in place to ensure that MBSE efforts are scoped to genuine business challenges and can be sustained across teams and departments.

Participants emphasized that interface modelling enables organizations to gain control over distributed development efforts, clarify responsibilities, and improve supplier collaboration. The abstraction provided by interface models helps teams visualize system interactions and identify integration risks early, even without committing to full MBSE adoption.

6.4.2 Conclusions

Modelling interfaces has emerged as a pragmatic and effective starting point for applying MBSE in brownfield development environments. During the workshops, industry participants emphasized that interface management provides immediate value by addressing integration challenges early in the development process. This approach enables organizations to gain control over distributed development efforts and supplier interactions, while also supporting contract management and traceability. A minimum-effort strategy focusing on high-risk or critical interfaces allows for manageable implementation and early success, which is essential for building momentum in MBSE adoption.

The interface-centric MBSE framework discussed in the workshops highlights the importance of clearly defining interfaces, establishing governance, and classifying interfaces to streamline interoperability. Interfaces serve as natural boundaries for assigning team responsibilities and ownership, which is particularly valuable in modular development environments with geographically distributed teams. By formalizing interface specifications in models, organizations can improve communication, reduce ambiguity, and ensure maintainability of decisions and rationale. This structured approach supports the creation of Digital Twins and standardized interface libraries, enabling reuse and consistency across product lines.

However, deploying MBSE—especially in an interface-centric form—requires careful consideration of organizational readiness. According to Conway's Law, system architectures often mirror the communication structures of the organizations that produce them. MBSE can help expose inefficiencies and guide necessary structural changes, but only if the foundational Systems Engineering capabilities are in place. In some cases, establishing reference architectures or enterprise-wide modelling strategies may be more appropriate initial steps. Differences in tooling and practices across sites, and limited control over supplier processes, may also hinder MBSE's effectiveness unless scoped to address specific business challenges, or tooling support provided for automatic conversion to "classic" document-based deliverables.

In conclusion, interface-centric MBSE offers a low-risk, high-impact entry point for organizations seeking to improve their systems engineering practices. It enables early value creation, supports long-term goals, and provides a structured pathway for broader MBSE adoption. Nevertheless, successful deployment depends on aligning technical ambitions with organizational capabilities, establishing governance, and ensuring stakeholder engagement across the development lifecycle.

7 Workshop 2: Variants & Diversity and MBSE

7.1 Introduction

The high-tech equipment industry relies on platform-based approaches, emphasizing reusable building blocks and product line engineering. Managing variability is central to delivering customized solutions based on shared platforms or components. These approaches are also known as reuse programs, product line architectures, or configure-to-order. All these types of product line engineering target reducing the R&D burden and speeding up time-to-market. The objective is to balance diversity and control, minimizing the creation of unique components while offering extensive product variations. Variability arises from two sources: features and components. Managing reuse is essential for composing products from platforms, requiring effective strategies to deliver maximum flexibility and efficiency with minimal cost, and fast time-to-market.

In this section, we look at strategies and aspects for using MBSE to manage variants and diversity of products. First a conceptual framework is presented, then the workshop questions and challenges are discussed, and finally the conclusion and outcomes of the MBSE phase 2 workshop 2 with this topic are described.

7.2 Conceptual Framework

To introduce the topic, TNO-ESI presented a conceptual framework addressing some key concepts on managing variants and diversity (see also [26]). This framework addresses the concept of product line engineering: developing a variety of products based on shared assets.

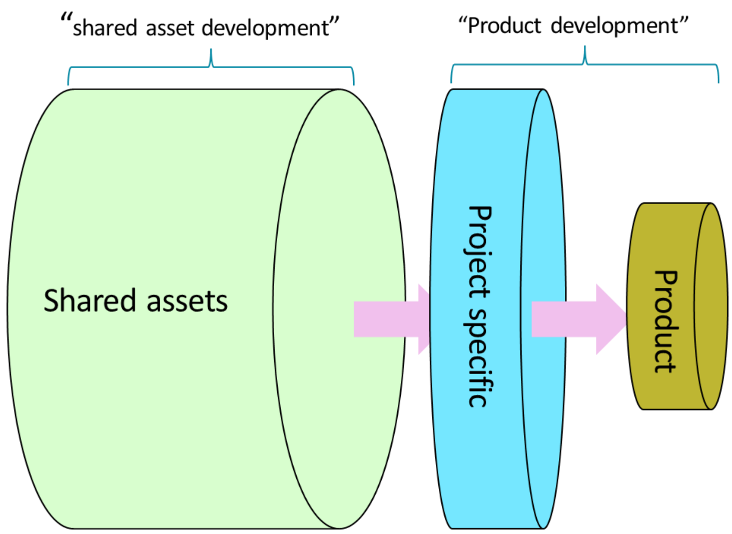

Figure 8 – Platforms (shared assets), projects, towards customer-specific products.

7.2.1 Variation management and platforms

A platform consists of a substantial set of shared assets that implement common functionalities and their variations within the defined scope of that platform, see Figure 8. This scope is determined by the range of products and the market segments the platform aims to cover. Projects then develop specific products by utilizing and configuring as many of the common components from the platform as possible. Any additional components required for the product are added specifically for that product.

The main goal of variation management in platforms is to exploit commonality:

- To reduce the integral cost over the total product lifetime, so not only during development but also in manufacturing, service, maintenance etc. Products are developed once, but are maintained, serviced, and updated for a long time.
- To manage integral costs effectively, the aim is to limit the number of supported variants while still offering sufficient variation to meet current and future market needs. The focus is not on the technical maximum of variation, but on what is necessary and relevant over time.

7.2.2 Features and Variations

It is important to establish the difference and commonality between features and variations. Features are “variations” in the functionality as offered to the customer. Variations are “variations” in the components, modules and building blocks of the product.

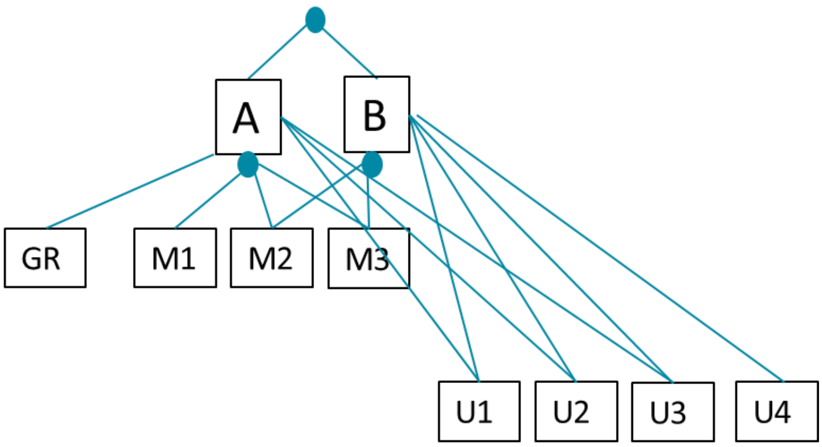

Figure 9 - An example feature tree.

Features usually form a feature tree as features may have dependencies. For a specific customer/product a set of features must be selected. A simple well-known example is putting together a car with its desired options, as many vehicle suppliers now offer through product configurators. Customers can select their desired package by traversing a feature selection tree and making choices at every knot. An example car feature selection tree could like Figure 9, as follows:

- Main series 2023 product variation “A” is the standard model while” B” is the station wagon variant.
- There are three different options for the UI (user console) for the normal car A (U1, U2, U3) and all four for the station wagon B.

- They share the seats and obviously have different bodies (not shown in the figure).
- There is an optional glass roof (GR - not available for the station wagon)
- There are three motor types available (M1, M2, M3), however the station wagon only uses types M2 & M3.
- Finally, there are four further add-ons that can be configured by choosing variants (seat heating, navigation, radio, DVD-player) – not shown in the figure.

There are many formalisms to describe a feature tree, an overview is given in [27].

Variations in the platforms/reuse context are all about diversity of components, modules and building blocks in the platform repository. Some components are part of each product; others are dependent on required features/performance. Components may have different (e.g., performance) variants. Finally, components may have (software) configurations/settings. Any product instance is built up from a subset of the available components and variants.

Obviously, there is mapping between the two (feature and component variations). When a customer or sales often use a "product configurator" to select features that under the hood selects the configuration of the components that will make up the product. Sometimes the mapping feature ←→variations is simple and one to one, more often a feature will define various configuration aspects for the modules.

7.2.3 Platform approaches to diversity management

Maintaining an overview of a sharply growing set of products, and component variations supported by a platform (and their relations and restrictions in application) is an increasing burden, while it is needed for R&D, sales, manufacturing, and service. Historically variations and feature and product trees are maintained in a company's PLM-system and commercial catalogue, while a variety of (in)formal Excel and other overviews are used within development, service, and sales to administrate them. A policy that inevitably leads to communication errors and inconsistencies.

Two principal approaches to managing diversity are the following:

- **150% model:** A top-down decomposition of all possible configurations.
- **Highly composable platforms:** a set of building blocks with an integration framework.

The "150% model" approach ensures that all variants for all products are combined in a single model that can then be used to select a configuration from. The well-known pure Variants [8] method approaches variation in this way. Typically, the automotive industry creates 150% models of their vehicle model lines to represent all possible buyer options given a standard product tree. This approach leads to a very large configuration space with many optional components. In this approach, a lot of constraints are required to reduce the number of variations to the desired set. Structure and constraints are to a certain extent exchangeable in variant modelling.

The "highly composable platform model" approach involves product families with high modularity, allowing end products to be flexibly composed from a set of (sub)components and variants thereof. In contrast to the "150% model" approach, no full set of options is prescribed. This highly composable platform model can lead to an explosion of variations, especially when components are structured in multiple levels with infinite possibilities, similar to a Lego-like solution.

However, companies prefer not to shift all integration and testing efforts to final product projects due to increased lead time and costs. Instead, they define a set of pre-integrated, supported variations that are tested and maintained: (partial) system configurations. These pre-integrated variants are chosen based on practical considerations like demand frequency and commercial value, with associated costs for maintenance, testing, and stock. So, typically a set pre-integrated component variants are defined (see also [28]), based on practical considerations.

7.2.4 Managing variations in platforms and product lines

For both platform approaches, variation management is a critical aspect of systems engineering when dealing with different configurations and options within a product family. It ensures that all potential variations are identified and managed efficiently. This is what organizations need to provide customizable and flexible products to their customers. Effective variation management helps maintain consistency, reduce complexity, and improve the overall quality of a system.

Key questions addressed in variation management are the following:

- What variations are supported and how?
- Are specific variations/extensions supported?
- How to maintain an overview of all variations?

Variation management aims to achieve maximum business value while controlling costs. It supports product diversification and variation management and aligns with platform-based development, where features and variations are strategically modelled.

In variation management, features are customer-facing variations in functionality, often organized in a feature tree. For example, car configurators allow customers to select options such as model type, UI options, and add-ons. Some features such as rear parking view require both a rear-view camera and a big screen only offered as part of the premium feature multimedia package.

In product lines and platforms, next to features, variations also involve components, modules, and building blocks in the platform repository. Components may have different variants and configurations. Product instances are built from a subset of these component variants. The mapping between features and component variations is crucial, often managed through product configurators.

7.2.5 Variant Modelling with MBSE

Variant modelling for (highly) composable platforms is required to manage the R&D of the supported variations, to assess product configuration possibilities, for maintenance and impact analysis. A common industry need is therefore to describe the set of variants as supported by the company's product line(s) in a consistent, clear, and accessible format. This especially applies to very modular (or composable) platforms that support much more variation than a specific product configuration tree. Modelling methods for variation modelling have therefore received considerable attention.

The formalization of the product variation tree removes inconsistencies, overlap and errors that are inherent to manual-maintained variation overviews. In addition, it opens opportunities for automatic checking and conversion into other formats, so removing manual steps and further potential sources of errors. As full formalization and definition in a tool allows for automation and scripting the variation model can serve as the often mentioned "authorative source."

With the introduction of MBSE in many companies, the use of models as a mechanism to formalize and maintain also product variation trees has gained traction. As MBSE in organizations is predominantly implemented through tooling based on the SysML formalism, it makes sense for many organizations to define a method to model product variation trees in SysML. Note that the SysML v1 language itself does not define any specific constructs or concepts for variation modelling. There are multiple methods and tools to describe variation outside the SysML domain though.

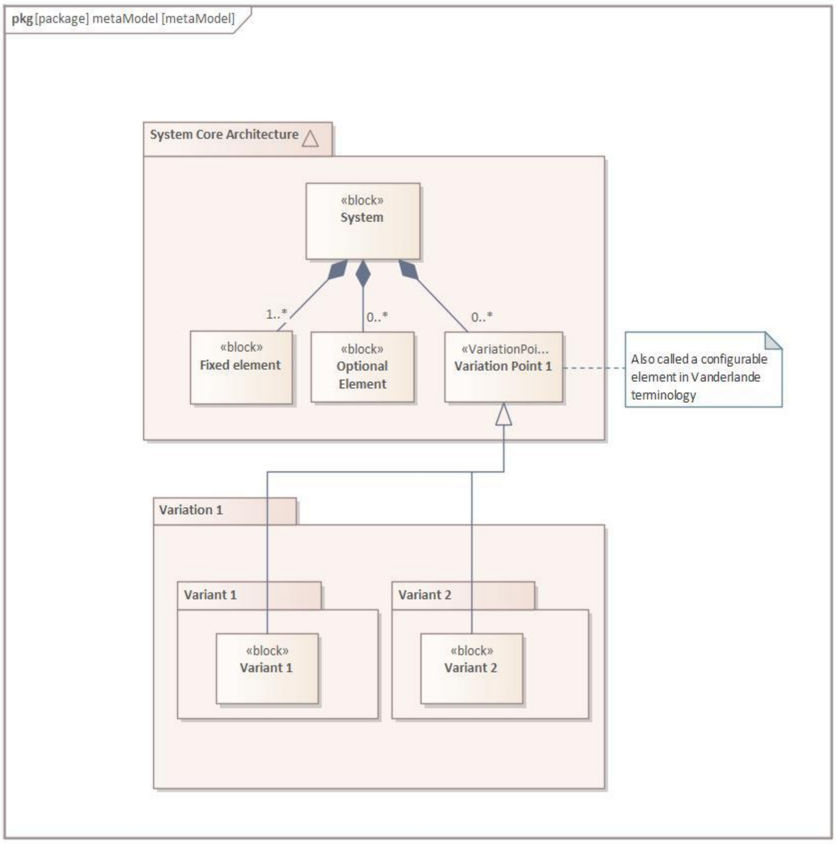

Figure 10 -the VAMOS structure.

One of the well-known methods for modelling a product variation tree in the SysML v1 formalism is described in the VAMOS (VAriation Modelling with SysML) extension defined by Tim Weilkiens [29]. This method is built around the following concepts:

- Any considered System of Interest has a core architecture that specifies all aspects of the system architecture, such as requirements, behaviour, structure, and parametric aspects or views. The core architecture contains all elements that are used in all valid system configurations. The elements of the core architecture are called core elements. The core architecture is stored in the Core package.
- The core architecture defines the system decomposition which includes fixed system elements, optional system elements, and variant elements.
- In the VAMOS method, variant elements are referred to as Variation Points. Variation Points serve as placeholders for alternatives which choice shall be made in concrete configurations of the system. Variation Points are always defined in the context of the system and are therefore defined within the core architecture in the Core package.
- Each variant element must be stored in its own Variant package.

- Several Variants of the same Variation are stored in one Variation package. In the VAMOS approach, all system variations and their variants are stored in the tree structure under the main system package.
- Each variant can have its own architecture; thus, a recursive top-down package structure occurs.
- Next to the core architecture, the model of the system considered may contain typical configurations.
- The set of valid configurations is constrained by the core architecture. The system model may only have several configurations (as typical examples) or no configurations at all, so that the specific configurations will be defined in the specific customer solution (project) scope.

The VAMOS structure (packages and structural) is depicted in the model as shown in Figure 10. Note that this is a fully recursive model allowing to detail the architecture and variants to an ever-lower level. Each Variant in its turn may have a core architecture and Variation Points again.

Outside the SysML domain, are many variation modelling methods exist such as e.g. Pure Variants [30] and various feature modelling tools/methods, see for an overview [31]. The European Space Agency has developed a language and tool agnostic system engineering information model for exchange of model data [32]. Some of these tools and methods can be integrated with MBSE tooling and methods like Capella or Cameo as an add-on.

Variation modelling in SysML v2. Finally, in the evolution of the SysML language, parts of the basic concepts behind the VAMOS method are now included in the SysML version 2 language [20]. SysML v2 is expected to be available in commercial tooling shortly, see also the recent book on Model-Based Product Line Engineering [33].

7.3 Questions and Challenges Discussed with Industry

The second workshop in the MBSE phase 2 study focused on the practical challenges and open questions surrounding the introduction and use of MBSE to manage product variants and diversity. Participants from across the high-tech equipment industry shared their experiences and concerns. Discussions were organized around four key themes: 1) technical aspects of product line engineering, 2) business implications, 3) integration across the product lifecycle, and 4) modelling methods and techniques.

7.3.1 How to use MBSE to improve Product Line Engineering: Technical aspects

Managing technical variation within product lines is a core challenge in high-tech equipment systems. MBSE offers structured modelling approaches to support the definition, configuration, and reuse of components and modules across product families. During the workshop, participants explored how MBSE can help clarify the boundaries between variants, support configuration logic, and maintain consistency across evolving platforms.

Key discussion points and challenges were the following:

- **Criteria for variants:** Determining whether a module or component should be treated as a variant depends on its functional and physical differences. Clear-cut criteria —such as whether the change affects system behaviour, interface compatibility, or lifecycle support— are necessary to consistently determine e.g. whether consider a module/component as a variant at logical or physical level.

- **Configurable parts:** Deciding whether configurable parts are treated as variants. For example, hardware shared across products but running different firmware may be modelled as either two variants or a single component with distinct instances. This decision affects traceability, reuse, and lifecycle management.
- **Model scope and release management:** Balancing granularity and version control is essential to support backward compatibility and flexibility. A recurring question was: “How do we manage model releases across product generations without losing traceability?”

MBSE can provide a foundation for managing technical variation, but its effectiveness depends on clear, and consistently applied, modelling policies and governance. The workshop emphasized the need for shared modelling conventions, governance and decision criteria to ensure consistent treatment of variants across teams and disciplines.

7.3.2 How to use MBSE to improve Product Line Engineering: Business aspects

Beyond technical aspects, MBSE value lies in support of business decisions around reuse, cost control, and product definition. Participants discussed how MBSE can help quantify the value of reuse, reduce unnecessary diversity, and align product definitions with market needs.

Key discussion points and challenges were the following:

- **Identifying Reusable Content (customer value).** Establishing when a variant justifies inclusion in a platform requires balancing engineering effort with business value. One question raised was: “How do we decide which variants are worth supporting long-term?”
- **Granularity of Product Definition.** The level of detail in product models affects flexibility and maintainability. Participants noted that overly detailed models can hinder reuse, while (too) abstract models may lack actionable insights. Balancing the level of detail to enable user flexibility.
- **Reduction of Variations (business perspective).** MBSE can help streamline the Bill of Materials (BoM) and reduce variation costs by identifying commonalities and enforcing constraints. A key challenge raised was: “How do we quantify the cost of supporting a new variant before committing to it?”

To show value, MBSE must bridge the gap between engineering and business by supporting decisions that balance flexibility, cost, and reuse. The workshop highlighted the importance of modelling strategies that reflect business priorities and enable portfolio-level reasoning.

7.3.3 What is the role of MBSE in the total PCP from Sales to Service

MBSE is often confined to engineering, but its potential spans the entire Product Creation Process (PCP): from sales to service. Participants explored how MBSE can support consistent product definitions, improve cross-functional alignment, and enable lifecycle traceability.

Key discussion points and challenges were the following:

- **Definition and consistency across disciplines**: Deviations in definitions of products and configurations between sales, development, and manufacturing may lead to costly re-work. MBSE can provide a shared product configuration definition model to ensure consistency across departments.
- **Cost Quantification:** Assessing the cost implications of supporting specific variants is essential for business planning and sales. Participants asked: “Can MBSE help simulate and compare lifecycle costs of different configurations?”
- **Governance and Team Alignment**: Effective MBSE deployment and MBSE-based variation management requires clear ownership of models and collaboration across teams with models. A key question was: “How do we ensure that all teams are aligned on variant definitions and responsibilities?”

MBSE has the potential to unify the PCP by providing consistent, traceable models that span disciplines and teams. The workshop emphasized the need for governance structures and shared modelling practices to realize this potential.

7.3.4 How to model variants and diversity: modelling methods and techniques.

Modelling variants and diversity requires robust methods that support reuse, configuration logic, and impact analysis. Participants discussed modelling strategies, tool support, and integration techniques to manage complexity and enable efficient customization.

Key discussion points and challenges were the following:

- **Reusing product variations and models.** Modular designs and clear extension points enable reuse across projects. Participants noted the importance of defining boundaries for customization to maintain model integrity.
- **Determining new vs. variant models.** A model is a variant if it builds on an existing design with modifications; it is new if it introduces fundamentally different structures. This distinction affects reuse strategies and model governance.
- **Combining platform and product models.** Aligning feature definitions and maintaining a shared repository for configurations is key to integrating platform and product models. Questions included: “How do we manage shared components across multiple product lines?”
- **Models for reuse** Both 150% models (supersets) and 100% models (specific configurations) may be valuable depending on context. When to choose which type is crucial. MBSE can help manage both types through structured modelling and constraint management.
- **Reuse of risk management.** Risk analysis frameworks such as FMEA and hazard analysis, and their results, should be reusable across platforms and product modules. MBSE can help link risk models to variant configurations for consistent safety assessments.
- **Validating interface specifications.** Structured reviews, simulation tools, and automated checks are needed to ensure interface specifications are complete and consistent. This is especially important when variants introduce new or modified interfaces.
- **Efficient derivation of variants.** Feature models and automation tools can assist in generating and validating variants quickly. Participants asked: “How can MBSE help us visualize the impact of feature selections on system architecture?”

- **Offering customizability.** Designing products with configurable modules or parameter-driven options supports customer-specific requirements. MBSE can help manage this complexity through formal modelling of constraints and dependencies.
- **Identifying and selecting variants.** Systematic analysis of feature requirements, market needs, and technical feasibility is needed to identify viable variants. Selection criteria include cost, performance, and customer preference.
- **Visualizing variant impact.** Visualisations, such as dependency graphs and heatmaps can help stakeholders understand how changes in features or components affect the overall system. This supports better decision-making and communication.

Effective modelling of variants and diversity requires structured and organisation-wide adopted methods, tool support, and governance. The workshop highlighted the need for scalable modelling strategies that support reuse, customization, and lifecycle traceability across complex product families.

7.4 Workshop Observations and Conclusions

Workshop discussions with the partners revealed two distinct patterns in how variation and Product Line Engineering (PLE) approaches are valued:

- **High-volume systems**: The importance of variation and PLE increases with production volume. In these cases, a long logistical lifecycle must be managed, including fluctuations in volumes and variants. Managing this lifecycle is a major challenge and falls under the domain of operational excellence.
- **Complex, low-volume systems**: For systems with high complexity and lower production volumes, the challenge lies more in balancing technical leadership and customer intimacy than in lifecycle management. These organizations focus on delivering tailored, high-performance solutions rather than optimizing mass production.

The TNO-ESI partners are predominantly positioned in the second category, where MBSE is leveraged to support engineering excellence and customer-specific innovation rather than large-scale lifecycle optimization. The following observations and conclusions apply therefore in the context of complex, low volume systems domain and engineering.

7.4.1 Workshop Observations

The second workshop in the MBSE phase 2 study focused on the challenges and opportunities of managing product variants and diversity in the high-tech equipment industry. Participants from the TNO partner network shared insights into how MBSE can support both technical and business goals in environments characterized by complex systems, evolving customer needs, and legacy constraints. The following observations summarize key themes that emerged during the workshop discussions.

- **Brownfield applications.** Implementing MBSE in legacy environments requires careful integration with existing processes, tools, and organizational practices. Rather than replacing current systems engineering practices outright, MBSE must be introduced incrementally to ensure continuity of innovation and engineering knowledge. Where to start with complex product lines?
- **Governance of product roadmaps**. Effective variation management depends on having stable reference architectures that guide product evolution. Clear differentiation between

feature enhancements and true product variants is essential to avoid unnecessary complexity and to maintain strategic alignment with business needs.

- **Configure-to-order systems.** MBSE supports configure-to-order strategies by enabling the reuse of parameterized components and streamlining the customization process. It can help reduce load on solution engineering teams by hiding irrelevant complexity when designing project-specific solutions out of platform components.
- **Supporting portfolio decisions.** In domains where systems are highly complex but produced in lower volumes, organizations face the dual challenge of maintaining technical leadership while staying closely aligned with specific customer needs. MBSE can support these organizations by better rationalizing portfolio decisions and facilitating the delivery of tailored solutions, all while preserving architectural integrity and traceability across evolving configurations.

These observations highlight that MBSE in the high-tech equipment industry domain must not only support cost reduction through variation control but also enable technical leadership and customer-centric development in contexts of low volume and high complexity.

7.4.2 Conclusions

The TNO partner network is predominantly engaged in low-volume, high-complexity domains, where SE and MBSE are used to support engineering excellence rather than mass production.

In this context, variation management and reuse are critical for these industries, offering customizable solutions on basis of platforms and incremental innovations. MBSE supports these efforts by providing structured methods to model, manage, and optimize product variations, ensuring alignment across technical and business domains while maintaining efficiency and reducing costs.

Introducing MBSE in brownfield, complex, low-volume applications requires an incremental integration approach and relies on stable reference architectures and differentiation between feature improvements and product variants. The workshop emphasized the need for pragmatic approaches, such as starting with interface modelling or feature trees, and highlighted the importance of business focus, governance, and stakeholder alignment.

8 Workshop 3: Critical to Quality & system behaviour and MBSE

8.1 Introduction

In today's high-tech landscape, equipment systems are composed of thousands of interconnected components, both tangible mechanical parts and intangible software elements. These systems operate within specific contexts and are designed to fulfil particular purposes [34].

Critical-to-Quality (CTQ) refer to the properties of a product, process, or service that directly impact its quality and are essential for meeting customer expectations. These challenges are often outlined in system contractual agreements through quality specifications, many of which are expressed as Key Performance Parameters (KPPs). Examples of KPPs include throughput, accuracy, and response times, which collectively indicate how effectively the system's dynamic behaviour achieves its intended functionality.

MBSE offers a structured approach in which engineers can create comprehensive models that represent the system's requirements, design, analysis, and verification processes. Such models can facilitate a deeper understanding of the system's behaviour and performance, enabling the identification of potential quality issues early in the development cycle. By iterative refinement and validation, MBSE then can help ensuring that the final system meets both technical specifications and customer expectations, enhancing overall quality and reliability. The third MBSE workshop focused on utilizing MBSE techniques to effectively manage Critical-to-Quality (CTQ) properties within systems engineering.

In this section, we look at strategies and aspects for using MBSE to manage CTQs and system behaviour in an organization. First, a conceptual framework is presented, then the workshop questions and challenges are discussed, and finally the conclusion and outcomes of the MBSE phase 2 workshop three with this topic are described.

8.2 Conceptual framework

TNO-ESI presented a conceptual framework addressing some key concepts on CTQ, system behaviour and MBSE.

- Critical-to-Quality and System Behaviour: CTQs are pivotal properties that influence a system's ability to meet quality and customer expectations. Understanding the interplay between CTQs and system behaviour is critical for ensuring the system's intended performance.
- Managing CTQs in Systems Engineering: One of the primary challenges in systems engineering is aligning CTQ attributes with organizational goals and priorities. Effective CTQ

management during development involves reasoning through modelling techniques that quantify quality parameters and their dependencies on system design.

- MBSE for CTQ and Dynamic System Behaviour: MBSE facilitates the integration of descriptive (qualitative) and analytical (quantitative) models to capture CTQs. This approach ensures consistency and traceability of CTQ properties across system artifacts and functional requirements. MBSE also supports the creation of a unified architecture that promotes collaboration among stakeholders.
- Value of MBSE and Analytical Models for CTQs: MBSE aids in model verification, validation, and governance, enabling virtual development and efficient impact analysis of CTQ-related decisions. These capabilities ensure that CTQ measures are tracked systematically, prioritizing quality attributes and aligning them with system objectives.

Many companies still face challenges in effectively modelling and managing CTQs. Key issues include dealing with incomplete models, identifying leading indicators, and fostering interdisciplinary collaboration. An integrated environment linking MBSE tools and domain-specific tools is essential for addressing these challenges. Unified architectures and simple, collaborative models can facilitate CTQ discussions among stakeholders.

8.2.1 Critical-to-Quality: A Six Sigma Concept

Critical-to-Quality (CTQ) is a quality concept stemming from Six Sigma, itself a set of techniques and tools for process improvement [35]. Six Sigma aims to identify and remove causes of defects and minimize variability in engineering and business processes with statistical quality management methods.

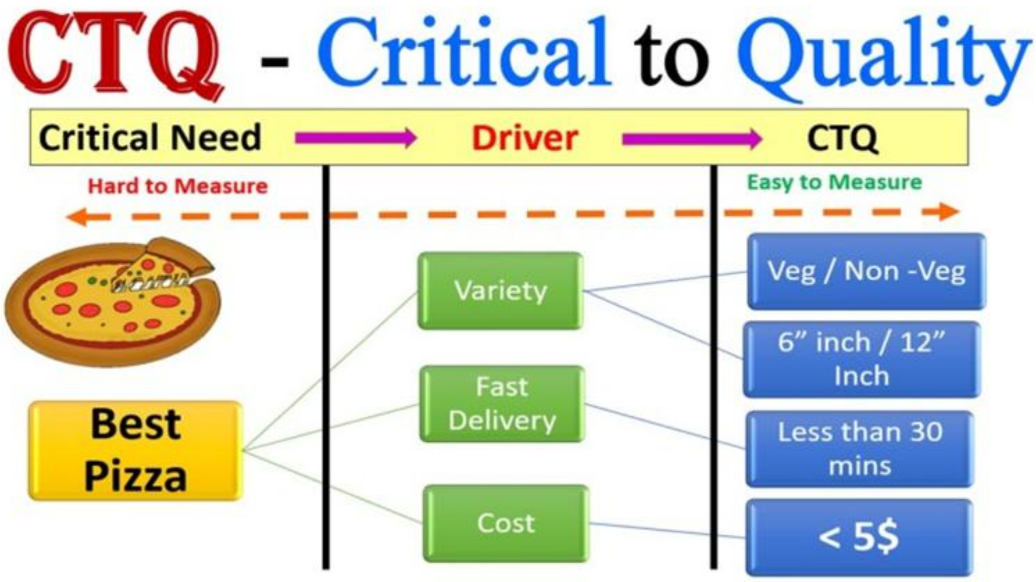

Figure 11 - Deriving CTQ properties for a pizza delivery shop example (source [36])

Within Six Sigma, Critical-to-Quality (CTQ) properties are those properties or attributes of a product or service that are essential for meeting the requirements or expectations of the customer. CTQ properties help a business understanding how to achieve a positive outcome from satisfied customers.

By building a Critical-to-Quality tree (see Figure 11), a business can convert broad yet critical customer needs into identifiable and measurable properties to drive a product or service. For example, to offer the “Best pizza in town,” a business should cater for a variety of offerings, with fast delivery at modest cost. These drivers then should be converted into measurable properties, such as specific vegetarian and non-vegetarian variants, pizza sizes, cost price and delivery time. Meeting these CTQ properties together then should meet the customer expectation of “Best pizza in town.”

Also in the high-tech equipment industry, a good understanding of CTQ properties is crucial to meet the requirements and expectations of the customer. Some examples of CTQs in this industry sector include the following:

- **Performance**: The ability of the product or service to meet its intended purpose or function
- **Reliability**: The ability of the product or service to perform consistently over time
- **Durability**: The ability of the product to withstand wear and tear
- **Convenience**: The ease of use or accessibility of the product or service
- **Aesthetics**: The appearance or design of the product
- **Safety**: The ability of the product or service to be used safely

Sometimes in Six Sigma context a differentiation is made in Critical-to-Customer (CTC) properties and further Critical-to-Quality (CTQ) properties, where the latter are then the organization-internal properties that need to be in place to meet the customer needs. In this conceptual framework, we do not make this distinction; we only refer to CTQ properties as those measurable properties correspond to the needs and expectations of the customer.

8.2.2 Impact of CTQ on System Development and CTQ Flow-down

A property being identified as a CTQ (or KPP) has an impact on many development aspects and phases, e.g. as follows:

- **Design**: When a property is identified as critical to quality (CTQ), it significantly influences the design phase. Designers must ensure that the product or process meets the CTQ specifications to satisfy customer requirements. This often involves rigorous analysis and optimization to balance functionality, cost, and quality. For instance, in designing a new product, engineers might prioritize materials and features that enhance durability and performance, directly addressing the CTQ properties.
- **Development**: During the development phase, CTQ properties guide the creation and refinement of prototypes and processes. Developers focus on achieving the desired quality levels by implementing robust testing and validation methods. This phase may involve iterative cycles of development and feedback to ensure that the CTQ requirements are consistently met. For example, software developers might conduct extensive usability testing to ensure that a user interface meets CTQ standards for ease of use and reliability.
- **Manufacturing**: In manufacturing, CTQ properties dictate the standards and procedures necessary to produce high-quality products. Manufacturers must adhere to strict quality control measures to ensure that each unit meets the CTQ criteria. This can involve advanced techniques, such as Six Sigma methodologies, to minimize defects and variability. For instance, in an automotive assembly line, CTQ properties might include precise tolerances for engine components to ensure optimal performance and safety.

- **V&V evidence**: Verification and validation (V&V) processes are crucial for demonstrating that CTQ requirements are met. V&V evidence includes documented proof that the product or process complies with the specified quality standards. This phase involves comprehensive testing, inspections, and audits to confirm that all CTQ requirements are fulfilled. For example, medical device manufacturers must provide detailed V&V reports showing that their products meet stringent regulatory standards for safety and efficacy.

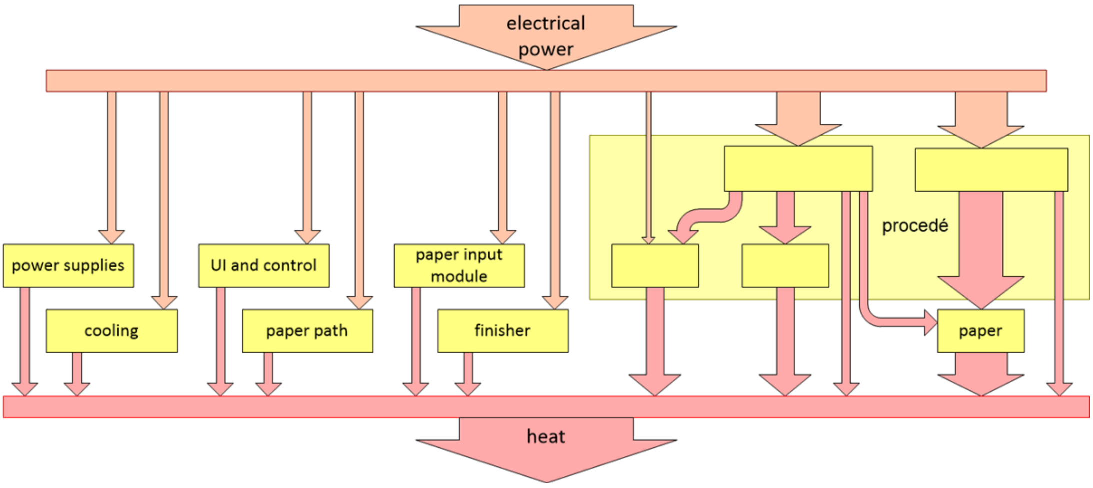

Figure 12 - CTQ flow-down example for electrical power budget of an office printer (source [37]).

CTQ flow-downs involve translating high-level CTQ requirements into specific, actionable lower-level requirements. This process ensures that every aspect of the product or process contributes to the overall quality goals. By prescribing and tracking CTQ contributions, organizations can maintain a clear focus on quality throughout the entire lifecycle. For instance, for the development of professional office printers, CTQ flow-downs might involve breaking down the overall electrical power requirements into specific component-level power specifications/budgets, ensuring that each part contributes to meeting the office-printer's peak power level requirement, as well heat production requirements (see Figure 12).

8.2.3 CTQ versus other Systems quality parameters

CTQ focuses on identifying key properties of a product or service that are essential to meet customer needs and expectations. These properties are derived from the Voice of the Customer (VOC) and are translated into measurable performance requirements. These in turn are broken down with CTQ-trees into specific, actionable, and measurable requirements.

In Systems Engineering (especially in the Defence domain) other terminology is frequently used to describe the critical need and system performance [38]. In that domain system users typically contract out the system design and build to contractors. In this acquirer/supplier relation the following terminology is used to capture the crucial needs versus system performance parameters (see also Figure 13):

- **Measures of Effectiveness (MOE)**: Operational success measures related to mission achievements, focusing on capabilities independent of technical implementation.
- **Measures of Performance (MOP):** Physical or functional attributes ensuring the system's capability and capacity to perform, assessed to meet design requirements and MOE.
- **Key Performance Parameters (KPP)**: Critical capabilities and properties with threshold values, essential for program success and considered Critical to Customer (CTC).

- **Technical Performance Measures (TPM):** Attributes assessing how well a system meets technical requirements, including design progress, compliance, and technical risk.

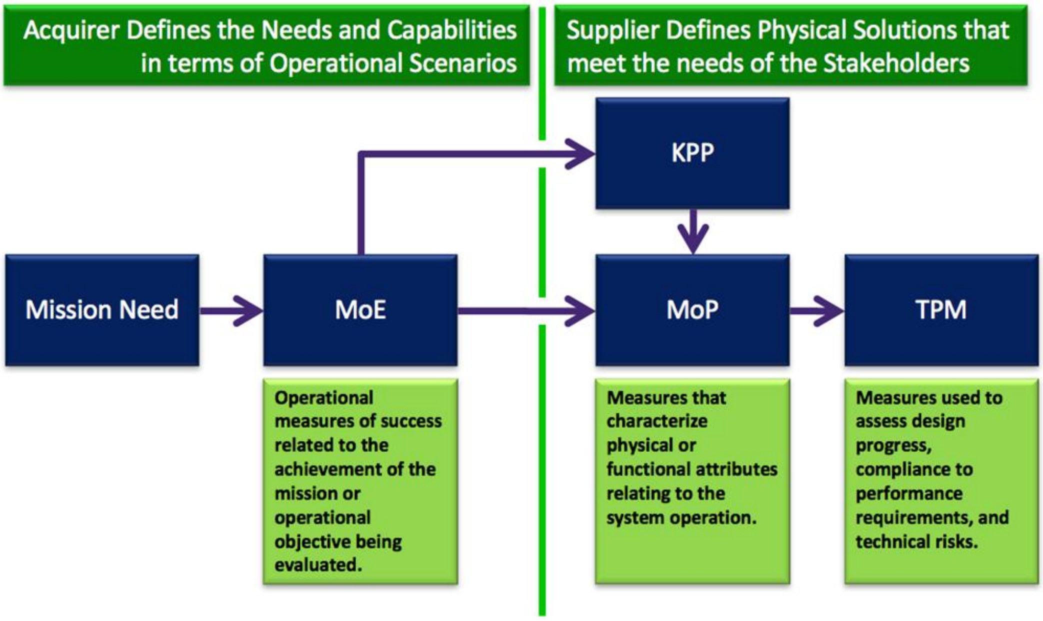

Figure 13 - Other definition of effectiveness and performance measures used in the SE world.

CTQs are most closely linked to Measures of Performance: these measures characterize physical or functional attributes, similar to how CTQ translates customer needs into specific product requirements.

Mission Need is similar to VOC; it represents the initial requirements or objectives that drive the entire process. MoE (Measure of Effectiveness) are comparable to CTQ, they define operational success criteria related to achieving the mission or objective.

8.2.4 Managing CTQs during system development

Managing Critical to Quality (CTQ) during system development involves several challenges in performing typical CTQ Work Items, as follows:

- **Identification & Flow-down:** Identifying CTQs accurately from customer requirements and ensuring they are properly cascaded down through all levels of the development process can be complex. Misinterpretation or loss of critical details during this flow-down can lead to unmet customer expectations.
- **Trade Space Exploration; Balancing CTQs**: Balancing multiple CTQs often involves trade-offs between competing requirements. This requires careful exploration of the trade space to find optimal solutions that satisfy all critical parameters without compromising overall system performance.
- **Change Impact Analysis**: Any changes in requirements or design can impact CTQs. Analysing these impacts comprehensively to ensure that changes do not negatively affect the critical quality attributes is crucial.

- **Verification & Validation (V&V):** Ensuring that CTQs are met through rigorous verification and validation processes is essential. This involves extensive testing and evaluation to confirm that the system meets all defined quality standards.

Maintaining overview and transparency on CTQs during development is essential for assorted reasons, including the following:

- **Actual Status.** Maintaining transparency about the status of CTQs throughout the development process helps in early identification of issues and facilitates timely corrective actions.
- **Traceability**. Ensuring traceability of CTQs from initial requirements through to final implementation and testing is vital. This helps in tracking changes, understanding their impacts, and ensuring that all quality attributes are consistently addressed.
- **Consistency (also with other CTQs)**. Maintaining consistency in how CTQs are defined, measured, and managed across various parts of the project ensures that all team members have a clear and uniform understanding of quality requirements.
- **Tribal Knowledge Made Explicit.** Converting implicit knowledge (tribal knowledge) into explicit documentation ensures that critical insights and expertise are not lost and can be shared across the team, enhancing overall project quality.

8.2.5 Analysing CTQs with models

Analytical and simulation models have long been used to analyse system performance and Critical to Quality properties. The purpose of the models (and the development phase in which they are used) significantly impacts their specificity. High-fidelity, detailed models are used when precise and accurate predictions are required, such as in the design of critical components where small deviations can lead to significant impacts. These models provide in-depth insights and are essential for rigorous validation and verification processes. Reduced order, aggregated models are employed when a broader overview is needed, such as in early design stages or when evaluating system-level trade-offs. These models simplify complex interactions, making it easier to explore various design options and optimize overall system performance. Examples of model types include budgets (mass, power, etc.), time-based simulations, transfer functions, and finite element models. Each type serves a specific purpose, from managing resource allocation to simulating dynamic behaviour and analysing structural integrity, ensuring that all CTQs are thoroughly evaluated and met.

Analysing CTQs often necessitates the integration of both system-level models and discipline-specific models to ensure a methodical analysis and optimization. System-level models provide a holistic view of the entire system, capturing interactions between various components and subsystems. These models are essential for understanding how various parts of the system work together. Discipline-specific models, on the other hand, focus on detailed aspects within specific domains such as structural analysis, thermal management, or electrical systems. Integrating these models allows for a more nuanced understanding of how individual components contribute to the system's CTQs, ensuring that all critical parameters are addressed.

Analytical and simulation models thus can help assess the feasibility of specifications by providing quantitative analysis of system parameters before the system is built. Such models assist in analysing CTQs and other key system qualities as follows:

- **Performance:** Evaluating whether the system can meet specified performance criteria under different conditions, ensuring it delivers the required functionality.

- **Reliability:** Ensuring that the system remains reliable and consistent across various scenarios, meeting stakeholder expectations.
- **Scalability:** Analysing how the system can scale to manage increased loads or expanded functionality, ensuring it can grow and adapt as needed.
- **Other System Qualities:** Assessing additional qualities, such as usability, compliance, and overall system efficiency, ensuring the system meets all defined requirements.

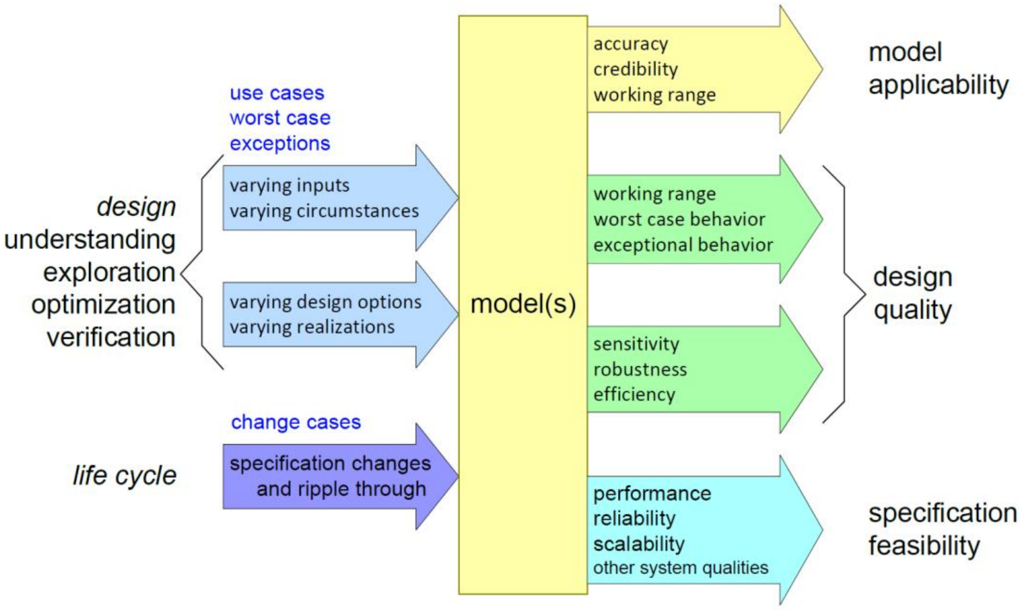

Figure 14 – Analysis with models: considerations and outcomes [39]

Besides assessing specification feasibility, analytical models can also analyse the design options and resultant design quality of the system. By variation of inputs, analytical models can analyse how such variations affect system performance, helping to optimize design choices and ensure that the system can manage a range of conditions effectively. Models contribute significantly to design quality by providing detailed insights into system behaviour, both expected and worst-case behaviour, and exceptions to identify sensitivities and potential failure modes. These then form input to develop mitigation strategies, enhancing system robustness.

Furthermore, during development requirements changes could occur, or design changes demand necessary due to e.g. supply chain changes. Analytical models can then assess the impact of changes in design or requirements on the system's performance. This helps in understanding how modifications affect CTQs and ensures that the system can adapt to evolving needs without compromising quality.

In doing so, understanding the model applicability is key in interpreting the analysis results. This involves considering model accuracy, which ensures that the model's predictions closely match real-world outcomes. The working range of the model must also be evaluated to determine the conditions under which the model provides reliable results. Additionally, model credibility is crucial, as it reflects the confidence stakeholders can have in the model's predictions based on its validation and verification against empirical data. Knowing the model's applicability helps ensure that the analysis results are both reliable and relevant to the system's design objectives and Critical-to-Quality (CTQ) properties.

8.2.6 Connecting models in MBSE to reason about CTQ properties

Developed and maintained stand-alone, analytic models may quickly become out of date with respect to an evolving design and engineering in development. Here, MBSE can significantly enhance overview and transparency on CTQs during development by maintaining consistency and real-time visibility into the actual status of CTQs through connected models. When done right, MBSE has significant potential to improve the engineering of CTQs. Analysing CTQs with MBSE requires connecting the two primary types of models: descriptive models and analytical models. These are explained below.

Descriptive models in MBSE are used to represent various aspects of a system in a detailed and interconnected manner. These models include elements that describe the system's structure, behaviour, parametric relationships, and requirements. They provide a comprehensive view of how various parts of the system interact and function together. Descriptive models are essential for understanding the system's architecture and ensuring that all components are aligned with the overall design and objectives.

Key aspects of descriptive models are the following:

- **Structure**: Defines the physical and logical arrangement of system components.
- **Behaviour:** Describes how the system operates and responds to different inputs and conditions.
- **Parametric:** Represents relationships between different parameters within the system.
- **Requirements:** Captures the specifications and constraints that the system must meet.

Analytical models in MBSE focus on quantifiable analysis and mathematical relationships within the system. These models use mathematical equations, such as differential equations, to analyse system parameters and predict performance. Analytical models are crucial for evaluating the system's behaviour under various conditions and for optimizing design choices based on quantitative data.

Key aspects of analytical models are the following:

- **Mathematical Relationships:** Uses equations to describe interactions and dependencies between system parameters.
- **Quantifiable Analysis:** Supports detailed analysis and predictions about system performance.
- **Optimization:** Helps in making informed decisions to enhance system efficiency and effectiveness.

Thus, descriptive models provide a detailed representation of the system's structure and behaviour, while analytical models offer a mathematical framework for analysing and optimizing system performance. Analytical models may use widely varying formalisms and algorithms, depending on the types of properties being analysed. These can range from Finite Element Models for structural and load bearing analysis, to electromagnetic models to timing performance models, to feedback control models.

Connecting descriptive and analytical models in MBSE for CTQ management. For analysing CTQs, both types of models are essential and need to be connected. Component and system variants and changes therein may percolate through the flow-down trees to top-level CTQs.

SysML models and the SysML (v1) language provide basics & linking 'hooks' for connecting such models in terms of Value properties, and Parametric diagrams / equations. Various MBSE tools offer further options for connecting models, as follows:

- **Integrated environment** (e.g. Dassault 3D Experience [40])
- **Design of Experiments tools** (e.g. Ansys ModelCenter [41])
- **Connector standards** (e.g. FMI [42], Comet [43], Mossec [44])
- **Connector facilities** (e.g. Capella [45] with Python4Capella Addon [46])
- **Export facilities** (e.g. SysML with XMI interchange standards [47])

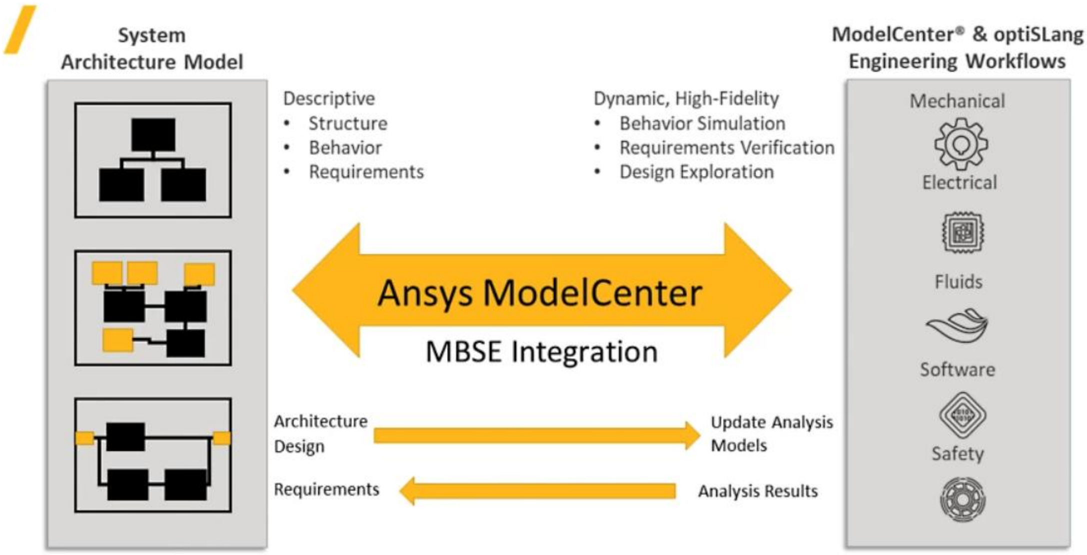

Figure 15. Connecting MBSE descriptive and analytical models (Ansys ModelCenter approach, source [41])

Integrated environments, such as Dassault 3D Experience [40], offer a unified platform where various models can coexist and interact, ensuring consistency and coherence across different system aspects. Design of Experiments (DoE) tools like Ansys ModelCenter [41] facilitate the exploration of multiple design scenarios by integrating analytical models with descriptive ones (see Figure 15), allowing for comprehensive analysis and optimization of system parameters.

Connector standards, such as FMI [42], Comet [43], and Mossec [44]) enable interoperability between different modelling tools and platforms, ensuring that models can be shared and utilized across various environments without loss of information. Connector facilities, like Capella [42] with the Python4Capella Addon [46], provide specific functionalities to link models through custom scripts and extensions, enhancing flexibility and customization. Lastly, export facilities using standards like SysML with XMI interchange also allow models can be exported and imported across different tools, maintaining traceability and consistency throughout the development lifecycle. Each of these options presents a way in MBSE to manage CTQ properties of complex systems over their lifecycle.

8.2.7 From models to virtual development

A further evolution in digital engineering is the transition from Model-Based Systems Engineering (MBSE) to virtual development. In MBSE, models are the primary means of information exchange, enhancing communication, consistency, and traceability across the development lifecycle. Virtual development takes this a step further by integrating advanced digital technologies to create virtual (or hybrid) representations of physical systems. Leveraging digital twins, digital threads, and high-fidelity simulations provide a more immersive and interactive environment for system development. This approach supports ‘system variants in the loop,’ allowing for the exploration of unique design configurations and their impacts on overall system performance. Additionally, with ‘environments in the loop’ simulation of various operational conditions are enabled, ensuring that the system can perform reliably under diverse scenarios. Virtual development enhances the ability to predict system behaviour, optimize performance, and identify potential issues early in the design process.

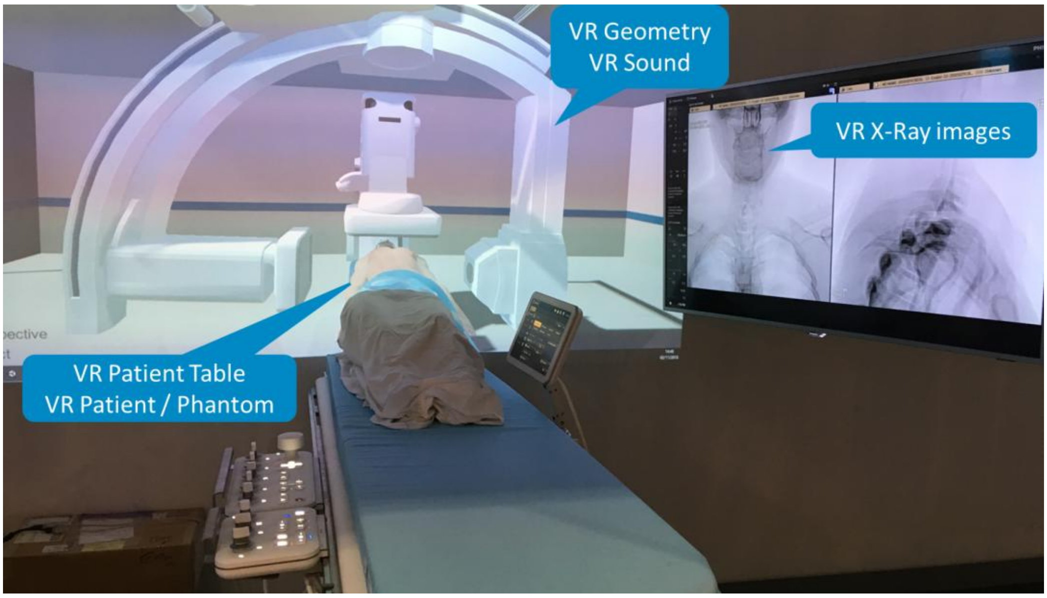

Figure 16 - Philips IGT virtual test platform.

An example of virtual development, a virtual test platform for an Image Guided Therapy system, is shown Figure 16. This virtual test platform [48], developed as part of the Enable-S3 project [49], is designed to enhance the development and testing of medical equipment. The platform provides a flexible test environment at the system level, supporting both manual and automated testing. It allows for multiple system configurations within a single virtual environment and enables fast switching between these configurations. This capability facilitates continuous automated testing, leading to higher test coverage, faster feedback to development teams, and quicker product releases. The platform mimics an image guided therapy system, and can be deployed fully virtually, but also hybrid as shown in Figure 16.

The virtual test platform integrates real and virtual components. In the development consequently, also virtual components must be tested against specifications and treated as first-class members of the product family. Required is to supports transparent communication between virtual and real components, allowing for seamless integration and testing.

Virtualization offers significant benefits in the development and testing of medical equipment. One of the most important advantages is the strengthening of communication between stakeholders. Additionally, virtualization enables earlier system access, allowing for usability testing before physical construction. This early access helps optimize design, facilitates design space exploration, and supports software testing for components still in development.

Further key benefits are cost reduction and improved handling of variability by allowing quick and automatic changes in system configurations. This flexibility is crucial in accommodating the diverse requirements of medical procedures and equipment. One such flexible virtual test platform can replace several physical test equipment configurations, reducing cost and footprint of test facilities.

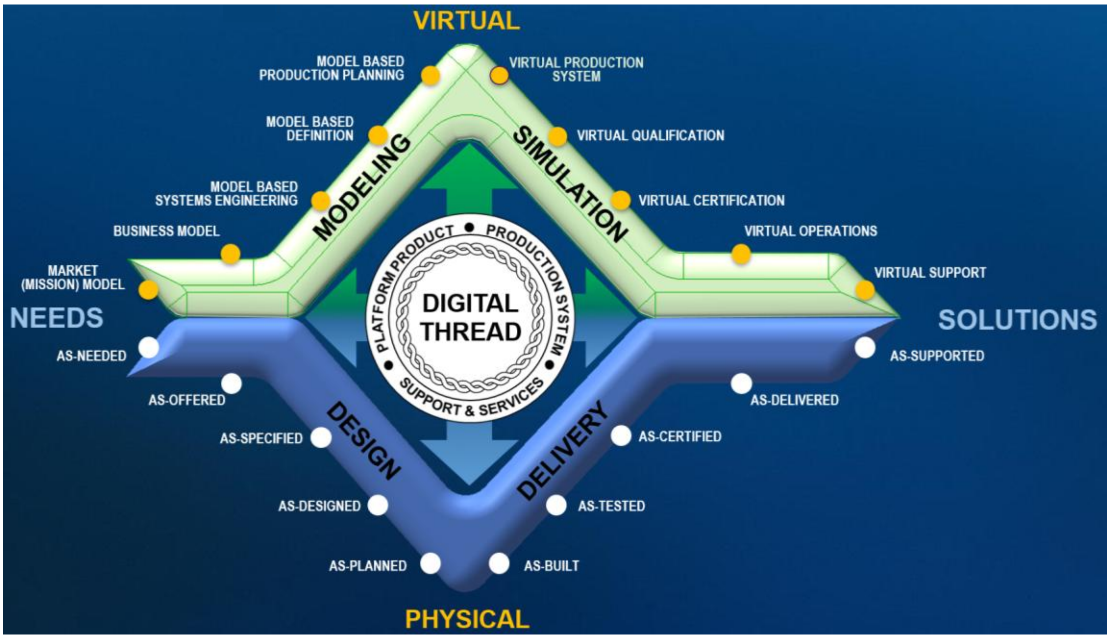

Figure 17 -The Boeing diamond vision for model-based engineering (source [50])

A further example of a virtual development approach is Boeing's digital transformation strategy. This strategy [50] is centred around the integration of physical and virtual systems through a model-based engineering (MBE) framework (see Figure 17). In this figure, the bottom half of the diamond-shaped graphic represents the traditional physical system engineering process, while the top half illustrates the virtual representation of these systems through modelling and simulation. The interior of the diamond symbolizes the digital thread, which links models and simulations to the physical system design, ensuring continuous and concurrent information exchange between the real and virtual worlds.

A significant challenge in implementing this strategy commercially is connecting to the supply network. Adopting industry standards rather than proprietary interfaces can help bring suppliers along in this digital transformation. It is recommended to facilitate seamless collaboration with suppliers, ensuring that all parties can work together effectively without being constrained by different tool sets. By defining a digital thread based on industry standards, Boeing aims to enhance interoperability and streamline the development process, despite the inherent difficulties in achieving this goal.

Successful deployment of virtual development thus requires careful consideration of several key aspects to ensure sustainable benefits. These include managing units of virtualization along managed system interfaces, establishing a product infrastructure that handles both real and virtual components, maintaining managed specifications for virtual components, ensuring virtual components are tested against their specifications, treating virtual components as first-class members of the product family, managing IP constraints with suppliers, and ensuring maintainability [48], [50].

In summary, successful deployment of virtual development requires long-term organizational commitment and collaboration with suppliers to justify investments and sustain the benefits.

8.3 Questions and challenges discussed with industry

The third workshop in the MBSE phase 2 study focused on the integration of Critical-to-Quality (CTQ) properties and system behaviour into MBSE practices. Discussions with industry partners revealed a wide spectrum of challenges, ranging from conceptual alignment to practical implementation.

Discussions were organized around three themes: i) CTQs and System Architecting, ii) Introduction, Awareness, Process, iii) Modelling and Data / Connecting Models. Below sections provide brief summaries of these discussion topics.

8.3.1 CTQ and System Architecting

The integration of Critical-to-Quality (CTQ) properties into system architecting was a central theme in the workshop discussions. Participants explored how CTQs can be used to guide architectural decisions, particularly in complex, low-volume systems where balancing technical leadership and customer-specific requirements is essential.

Key discussion points and challenges were the following:

- What role should CTQ reasoning play in system architecting processes and in balancing technical leadership with customer intimacy? Embedding CTQs into early design decisions and maintaining traceability throughout the lifecycle enhances the coherence and robustness of system architectures. Such integration (see e.g. [51] for performance engineering) supports informed trade-offs and ensures alignment with stakeholder expectations.
- In what ways can CTQs be embedded as architectural drivers in system-level models to drive system level decisions? Their integration into architecture models can help align technical leadership with customer expectations. Achieving this requires consistent modelling practices across disciplines and a shared understanding of quality priorities.
- How can system architects use models effectively to reason about CTQs in complex, low-volume systems? Tailoring solutions to specific needs while maintaining architectural integrity is a key architectural concern. This calls for a modelling approach that supports both flexibility and rigour across the development lifecycle.
- How can incomplete or qualitative models be validated during early design phases? These models often rely on empirical data or expert judgement, making it hard to assess their completeness. Integrating such models into MBSE workflows requires flexible modelling approaches that accommodate uncertainty and evolving knowledge.
- What are the barriers to linking CTQs to functional requirements in MBSE environments? Without clear traceability, it becomes difficult to justify design decisions based on quality attributes. This limits the effectiveness of CTQ reasoning in guiding system development and compromises the coherence of architectural choices.

The discussions highlighted that embedding CTQs into system-level models requires more than technical capability—it demands consistent modelling practices, early design integration, and a shared understanding across disciplines. Addressing these challenges will be key to enabling robust, traceable architectures that support both innovation and quality assurance.

8.3.2 Introduction, Awareness, Process

A recurring theme in the workshop was the organisational readiness required to adopt CTQ modelling effectively. Participants examined how awareness, training, and structured processes contribute to the successful integration of CTQ reasoning into MBSE practices.

Key discussion points and challenges were the following:

- How can organisations set clear, yet feasible goals and scope for CTQ modelling? Ambiguity in objectives can lead to fragmented efforts and inconsistent outcomes. A structured process helps maintain focus and coherence throughout the modelling activities.
- How can organisations build shared awareness, competence, and alignment in CTQ modelling across teams? Variability in understanding affects the consistency and depth of CTQ integration into MBSE practices. Building shared understanding through training and collaboration is essential to foster effective adoption.
- What mechanisms can support iterative refinement of CTQ models? Establishing feedback loops allows organisations to capture lessons learned and update models based on new insights. Such refinement enhances model relevance, accuracy, and long-term value.

Participants concluded that fostering a culture of proactive quality design, supported by clear goals and iterative refinement, is essential for a sustainable CTQ deployment. Organisations must invest in competence development and process alignment to ensure that CTQ modelling efforts will deliver long-term value.

8.3.3 Modelling and Data / Connecting Models

The integration of models and data across tools and domains remains a central challenge in the adoption of MBSE practices. Workshop discussions highlighted several recurring questions and concerns that reflect the complexity of achieving model connectivity, data consistency, and effective CTQ reasoning.

Key discussion points and challenges were the following:

- How can models be effectively connected across tools and domains? Participants noted that interoperability issues continue to hinder the seamless exchange of data and insights between modelling environments. The lack of standardised connectors and integration frameworks makes it difficult to maintain consistency and traceability. As one participant phrased it, 'How to connect models and data?' remains a pressing concern that requires coordinated technical solutions.
- What model views are needed to support CTQ reasoning and decision-making? Multiple model views are essential for understanding how quality attributes propagate through the system and affect design choices. Stakeholders require perspectives that support impact analysis and facilitate interdisciplinary collaboration. The challenge lies in defining and maintaining these views in a way that aligns with both technical and organisational needs.
- How can data consistency be ensured across interconnected models? Maintaining coherence and traceability across models is critical to avoid misinterpretation and design errors. Discrepancies in data representation can undermine confidence in MBSE outputs and hinder validation efforts. As highlighted in the workshop, 'How to link information from different tools?' reflects the broader need for robust validation mechanisms and shared data standards.

The challenges discussed in this theme underscored the importance of interoperability, model clarity, and data integrity in MBSE environments. Addressing these issues will require coordinated efforts to establish shared standards, improve tool integration, and support multi-view modelling that reflects the complexity of CTQ reasoning.

8.4 Workshop Observations and Conclusions

The discussions in third workshop on CTQ and system behaviour in MBSE showed a shared motivation to incorporate CTQ reasoning into MBSE practices, while also exposing the practical hurdles that organizations face. Most organisation still were focusing their MBSE efforts on descriptive modelling. In this section, the observations and conclusions from this workshop are summarized.

8.4.1 Workshop Observations

The following observations summarize key themes that emerged during the workshop discussions.

- Critical-to-Quality (CTQ) attributes are commonly recognized as crucial architectural drivers, influencing key system design decisions. In the complex, low-volume environments of the high-tech equipment industry, managing CTQs is essential for balancing technical leadership with customer intimacy. The challenge is delivering tailored, high-performance solutions that meet customer expectations while maintaining architectural integrity.
- Flowing down CTQs from system level to component level is seen as essential for maintaining alignment and ensuring that quality attributes are properly addressed throughout the development process. Participants stressed the importance of traceability to support this flow-down, enhance transparency, and facilitate quality assurance across system levels.
- Many organizations are still in the early stages of MBSE, focusing mostly on descriptive representations of systems, rather than modelling system behaviour and quality attributes. Complementing and connecting descriptive representations with analytical models that support simulation and quantitative analysis of system behaviour CTQs is seen as a necessary next step to further achieve value with MBSE.
- Connecting descriptive MBSE models with analytical models remains a challenge. Participants discussed various integration strategies, including the use of connector standards and integrated platforms. Effective model connectivity is essential for maintaining consistency and enabling real-time data exchange.
- Successful CTQ modelling requires interdisciplinary awareness and competence. Several organizations noted that internal deployment is hindered by a lack of shared understanding, insufficient training, and limited exposure to MBSE practices. Building organizational readiness is critical for the long-term success of MBSE initiatives supporting effective CTQ modelling and analysis.

The workshop discussions underscored that CTQ modelling is not merely a technical challenge but a systemic one, requiring alignment across tools, teams, and disciplines. While MBSE tools and methods offer a structured basis for CTQ modelling and analysis, the full potential for CTQ reasoning can only be realized through integrated environments, well-defined processes, and sustained organizational commitment. Achieving this requires not only technical interoperability but also a shared understanding across disciplines and consistent engagement throughout the organisation.

8.4.2 Conclusions

Critical-to-Quality (CTQ) are those properties of a product, process, or service that have a direct impact on its quality and are crucial to meeting customer expectations. System contractual agreements invariably involve quality specifications, many expressed as Key Performance Parameters (KPPs), such as throughput, accuracy, and response times, which reflect how well the system's dynamic behaviour realizes its intended functionality.

The workshop highlighted ongoing challenges in industry, such as managing incomplete models, identifying effective leading indicators, and structuring CTQ modelling in a way that supports decision-making across disciplines. There is a clear need for interdisciplinary collaboration, unified architectures, and integrated environments to manage diverse models and data across hardware, software, and tooling domains.

MBSE offers a promising foundation to address these challenges by enabling early and continuous assessment and V&V through simulation and co-simulation, with approaches such as ModelCenter [41], FMI [42], Comet [43], and extended into virtual and mixed prototyping by (automotive) platforms such as AVL's Integrated and Open Development Platform (IODP) [52]. These approaches show that CTQ modelling can be embedded into MBSE models from the outset, allowing for iterative refinement and validation throughout the development lifecycle.

Even with the increasing availability of advanced MBSE tools and simulation platforms, the credible simulation and analysis of Critical-to-Quality (CTQ) properties and dynamic system behaviour remains a significant challenge for complex systems. Models for such systems are inherently elaborate, often requiring multiple versions at different levels of fidelity, ranging from high-fidelity, domain-specific analyses to reduced-order, system-level representations [53]. Validating these models across domains and abstraction levels is difficult, as each version may rely on distinct assumptions, data sources, and integration pipelines. Thus, despite the progress in tooling, the ability to build and maintain models that are both credible and predictive for CTQ reasoning is far from trivial.

Key takeaways of this workshop include the significance of CTQs in defining and ensuring system quality, and the importance of connecting descriptive and analytical models. MBSE can play a significant role in supporting traceability, consistency, and stakeholder alignment. To fully realize these benefits, organizations must invest in flexible modelling strategies, tools, and tool interoperability [54]. Furthermore, they must strive for a shared understanding in the organisation and instil structured processes and that support CTQ reasoning across system levels and disciplines.

9 Workshop 4: MBSE embedding and introduction

9.1 Introduction

Introduction of MBSE, as part of an organization's digital transformation requires "an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal" [55] [56]. Besides the introduction of tools and methods, this means that a lot of attention and effort needs to be spent on the creation of organizational capabilities. To achieve the benefits from digitizing (systems) engineering, just introducing MBSE tools and the associated methods does not suffice.

In this section, we look at strategies and aspects for introducing and embedding MBSE in an organization. First, a conceptual framework is presented, then the workshop questions and challenges are discussed, and finally the conclusion and outcomes of the MBSE phase 2 workshop four with this topic are described.

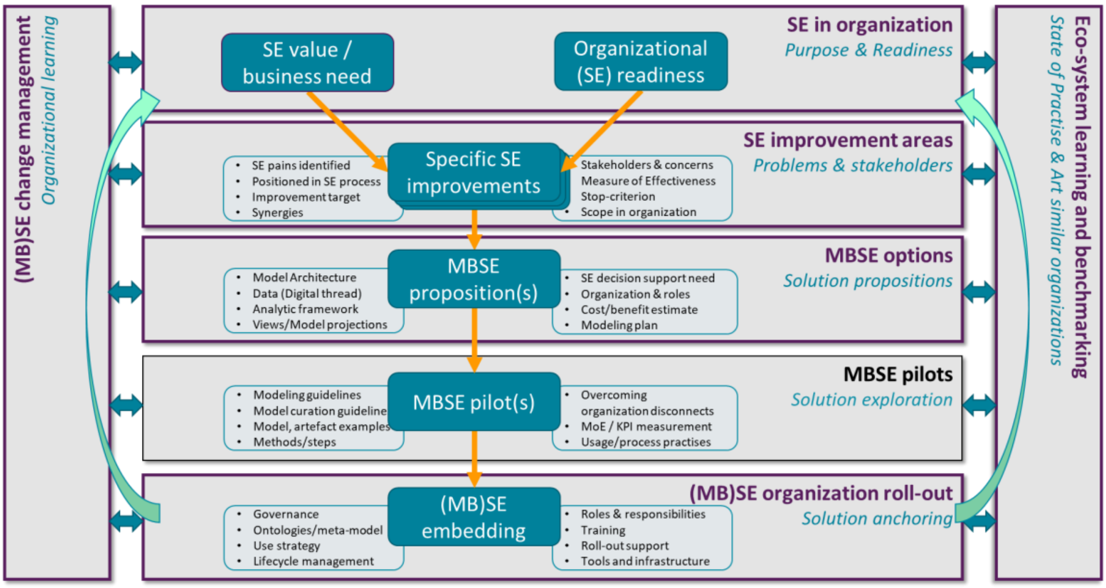

Figure 18 – Reasoning line to guide introduction of MBSE in an organization.

9.2 Conceptual framework

How to guide (and anchor) an introduction of MBSE in an organization? Experience has learned that achieving/perceiving value with MBSE is far from trivial [57] [58]. In this section, a conceptual framework is presented, which consists of a reasoning line and a number of key questions to be considered for introducing MBSE. TNO-ESI created this reasoning line (see Figure 18), as part of the MBSE study phase 1. The reasoning line considers both technical and organizational aspects for MBSE to add value, as well as the need for MBSE to be embedded in an SE way-of-working.

9.2.1 MBSE introduction reasoning line

Introduction of MBSE is a complex change process affecting many parts of an organization, and how they collaborate. The reasoning line, as shown in Figure 18, considers seven main viewpoints to guide, customize, and rationalize a value-add introduction of MBSE, and are annotated with relevant technical and organizational aspects to be considered.

- The first viewpoint looks at the state of **SE in the organization**: its SE readiness and the business need for change. An organization must be capable of doing SE, before embarking on MBSE. Also, the intended change must be rooted in a clear business need / value improvement.
- Secondly, **SE improvement areas** should be understood and identified, i.e., the "problem space" [59]. What are the SE pains? Which stakeholders experience these? What part of SE needs to be improved, how much; when to stop (and, when is good, good enough)? Also, which part(s) of the organization should be involved? Do the outcomes address the real needs of "outside" beneficiary stakeholders (e.g., sales, service, lifecycle)?
- Thirdly, based on rationalized and scoped SE improvements, a selection can be made where **MBSE options** could add value. For those, value propositions should be defined, including the SE support targeted, and how to achieve this with MBSE (which model(s), analytic framework, data etc.), but also how to organize and plan this, with a cost/benefit analysis. An overview of potential MBSE value options (benefits) is given in [11].
- Fourthly, **MBSE pilots** then can explore the effectiveness of these options, and measure / assess benefits. Pilots can also refine methods, provide (input for) guidelines. Pilots may encounter organizational issues and disconnects exposed by a more formal way-of-working. Such pilots should be positioned preferably in the main stream of the work, replacing traditional workflow, but first in a non-critical part of the project, such that trust can be gained from its application.
- Fifthly, **(MB)SE organization roll-out** needs to ensure that the MBSE way-of-working is indeed sustained by embedding it in the organization. This requires governance, ontologies/meta-models, tools, and infrastructure, but also training, and definition of (new or changed) roles and responsibilities.
- These activities should be supported by two further activities: i) general **(MB)SE change management** to ensure that organizational learning and a change in SE culture takes place, and ii) **Eco-system learning / benchmarking** to ensure lessons learned in similar organizations are incorporated, not duplicated.

Introduction of MBSE is a complex change process affecting many parts of an organization, and how they collaborate. This reasoning line aims to provide guidance to MBSE introduction in the High-Tech Equipment Industry but has wider applicability. It can be used as a check for rationalization of activities: not to be mistaken for a process [60]. Having a clearly articulated purpose, and rationalization of MBSE activities is crucial to gain organizational support, achieve value, and for MBSE to be firmly embedded in an SE way-of-working.

The following subsections elaborate the reasoning line with a number of key questions to be addressed when introducing MBSE in an organization. These questions (Why, What, Who, Where, How) and approach stem from lessons learned at ESA, the European Space Agency [61].

9.2.2 WHY introduce MBSE?

When considering introducing Model-Based Systems Engineering (MBSE) in an organization, it is crucial to understand the purpose and goals of MBSE deployment: what specific SE improvements are sought or needed?

In larger organizations with complex products, there is typically an ongoing battle between time, quality, complexity, and cost throughout a system's or product line's lifecycle. The key to managing these factors more effectively lies in improving communication and collaboration by making Systems Engineering more effective.

Enhancing communication is a significant area where MBSE can contribute to making Systems Engineering more effective, especially in larger organizations. This includes ensuring that different engineering teams can share and understand each other's work seamlessly, facilitating smooth transitions and information flow from one phase of the project to the next, maintaining clarity and coherence in communication from the highest system level down to individual components, and ensuring that all stakeholders, from customers to suppliers, are on the same page.

Key potential improvements in enhancing communication with MBSE are the following:

- **Time**: MBSE can support increasing the frequency of communication, ensuring that all team members have access to consistent and up-to-date data. This iterative approach helps keep everyone aligned and responsive to changes.
- **Quality**: MBSE can help continuously enhance the confidence in the information exchanged. Reliable and accurate data are essential for making informed decisions.
- **Complexity**: MBSE can aid in developing the ability to communicate complex ideas succinctly. This involves using appropriate levels of abstraction and depth, tailored to the purpose of the communication.
- **Cost**: MBSE can focus on early detection and prevention of potential problems, significantly reducing costs associated with late-stage changes or rework. Identifying issues early in the process is key to managing costs effectively.

When considering introducing MBSE in an organization, it is essential to first evaluate whether the organization's Systems Engineering (SE) capability is mature enough to effectively integrate and utilize the new methodologies and tools that MBSE offers. Given that, it is advisable to start by identifying the primary cost and time drivers within the organization: the SE value/business need in Figure 18. Understanding the business needs and drivers will help in tailoring an MBSE approach to address the most critical aspects effectively.

Thus, **two key questions to consider upfront** are the following:

1. **What is the main cost driver?** Determine the factors that contribute most significantly to the overall costs. This could include late-stage changes, rework, or inefficiencies in the development process.
2. **What is the longest time driver?** Identify the processes or phases that take the most time to complete. This could be due to lengthy approval processes, complex integration steps, or extended testing periods.

Understanding the main cost and time drivers offers a clear business rationale for enhancing system engineering practices. This understanding provides a basis for implementing MBSE, as it highlights the areas where MBSE can have the most significant impact.

9.2.3 WHAT to achieve with MBSE?

Once the main cost and time drivers are identified, the next step is to evaluate how MBSE can specifically improve these two aspects: *what are the potential MBSE propositions* (see Figure 18). The focus should be on how MBSE can streamline processes, enhance communication, and reduce inefficiencies related to the identified cost and time drivers.

While the primary focus should be on the main drivers, it is also important to recognize the additional benefits that MBSE can bring. These may include enhanced understanding and communication, enhanced consistency, and overall system quality. See also [11] for an elaborate overview of potential MBSE benefits. For these main benefits, this is how MBSE can contribute to them as follows:

- **Enhanced Understanding and Communication:** MBSE offers a clear and standardized approach to creating models that represent real-world abstractions. This explicit notation is crucial for accurately capturing the system's requirements, design, and behaviour. By doing so, it facilitates better understanding and communication among stakeholders, ensuring everyone is aligned and informed about the system.
- **Continuous Verification for Internal Consistency**: One of the key strengths of MBSE is its ability to continuously verify the model for internal consistency. This involves regular checks to ensure the model is correct and complete, significantly reducing the risk of errors and inconsistencies within the system design. A backlog of issues can provide insight into the technical debt, indicating model maturity. This ongoing verification process helps maintain the integrity of the model throughout its lifecycle.
- **Validation for External Consistency**: MBSE also provides robust mechanisms for validating of models to ensure they meet requirements and constraints towards external parties, e.g. with respect to formats and profiles. This validation process is essential for confirming that the model fulfils its intended purpose. By validating models against external criteria, MBSE ensures that the model is both effective and usable by external parties.

To ensure the successful implementation of MBSE and realizing these benefits, it is crucial to continuously monitor and adjust the approach based on ongoing insights: Revisit the main cost and time drivers periodically to ensure they are being effectively managed. Adjust the MBSE strategy as needed based on the latest data and insights. Involve all stakeholders and actively manage perception: Engage all relevant parties in the process and ensure they understand the benefits and progress of MBSE implementation.

Thus, when considering the introduction of MBSE, it is advised to focus on the primary cost and time drivers. By addressing these critical aspects first, organizations can effectively leverage MBSE to improve overall efficiency, quality, and collaboration. These primary cost and time drivers may NOT necessarily be the parts that are the most complex. If so, a solid business case may exist with low lead time to value, i.e. "quick wins". Establishing a targeted approach not only helps in managing the most pressing challenges but also allows for the recognition and management of secondary benefits that come with deploying MBSE.

To ensure a successful transition, it is important to start with high-leverage actions that provide early successes. This involves understanding and addressing the key change agent aspects: pains, gains, comfort, and fear. By systematically evaluating these factors, organizations can create a structured and supportive environment for MBSE implementation: this is addressed in “WHERE to start?”, Section 9.2.5. This incremental approach helps in achieving intermediate wins, securing support from both senior management and staff. For realizing the full potential of MBSE, it is also imperative to understand who to involve in stakeholder management besides senior management and staff. This is addressed next.

9.2.4 WHO to involve?

Introducing Model-Based Systems Engineering (MBSE) is a significant organizational change that necessitates the involvement and support of various stakeholders. Effective stakeholder engagement is essential for the successful implementation of MBSE, as it ensures that everyone understands the benefits, challenges, and processes involved. Organisation-wide change management hence is important.

Engaging stakeholders early and consistently helps build a shared vision, foster collaboration, and gain buy-in from various levels of the organization. This approach facilitates smoother transitions, reduces resistance to change, and enhances the overall effectiveness of the MBSE initiative. Here are the key steps to ensure effective stakeholder engagement:

- **Identify All Stakeholders**: Begin by identifying all the stakeholders who will be impacted by the introduction of MBSE. This includes individuals and groups across different departments and levels within the organization, such as engineering teams, project managers, executives, and external partners.
- **Assess Stakeholders' Position in the Adoption Cycle**: Evaluate where each stakeholder is in the adoption cycle using the ADKAR method (Awareness, Desire, Knowledge, Ability, Reinforcement). This assessment helps in understanding their readiness for change and tailoring the communication and training efforts accordingly.
- **Identify Holders of the Need**: Determine who within the organization has the most pressing need for MBSE. These are typically the individuals or teams facing challenges that MBSE can address, such as complex system integration issues or inefficiencies in the development process.
- **Identify Holders of the Budget:** Identify the stakeholders who control the budget and financial resources necessary for implementing MBSE. These may not necessarily be the holders of the need, yet gaining their support is crucial for securing the funding required for training, tools, and other resources.
- **Organize Your Stakeholders**: Organize the identified stakeholders into groups based on their roles, influence, and level of involvement in the MBSE implementation. This helps in managing communication and engagement efforts more effectively.
- **Train Your Stakeholders**: Provide comprehensive training to all stakeholders to ensure they understand the principles, benefits, and practical applications of MBSE. Tailor the training to address the specific needs and knowledge levels of different stakeholder groups.
- **Communicate Effectively**: Adapt the communication strategy to the adoption status of each stakeholder. Ensure that the messages are clear, relevant, and address the concerns and expectations of the stakeholders. Regular updates and transparent communication are key to maintaining engagement and support.
- **Be Realistic and Firm**: While it is important to highlight the benefits of MBSE, avoid overselling. Be realistic about the challenges and the time required for full

implementation. However, remain firm and consistent in conveying the core message about the value and importance of MBSE.

- **Support and Encourage**: Instead of pushing stakeholders to adopt MBSE, offer support and assistance to help them understand and embrace the change. Provide resources, address concerns, and demonstrate the practical benefits. Once stakeholders are on board, encourage them to actively participate and contribute to the successful implementation of MBSE.

Introducing Model-Based Systems Engineering (MBSE) is an organization-wide change that requires the involvement and support of various stakeholders. By actively involving stakeholders, one can leverage their insights, address their concerns, and create a supportive environment that drives the successful adoption and integration of MBSE.

9.2.5 WHERE to start?

Digitalizing the engineering workflow with MBSE is a complex change process that requires careful management. Understanding the main cost driver and the longest time driver is crucial for effectively navigating this transition. Realizing the full potential of MBSE involves a lengthy transition process and significant upfront investment. To justify this transition and secure support from both senior management and staff, it is imperative to achieve intermediate wins and successes. Therefore, careful consideration of where to start, and identifying high-leverage actions that provide early successes is advised. By understanding and addressing the following four key change agent aspects (PGCF: pains, gains, comfort, and fears), an incremental and successful introduction of MBSE can be achieved:

- **Pains**: Identify the challenges and inefficiencies in the current way of working ("Ist"). These are the factors that push the organization away from its existing processes. Examples include inflated costs due to late-stage changes, prolonged development cycles, and communication breakdowns. Recognizing these pains helps in understanding the urgency and necessity for change.
- **Gains**: Determine the potential solutions and benefits that MBSE offers ("Soll"). MBSE can streamline processes, enhance communication, and reduce inefficiencies, directly addressing the main cost and time drivers. The gains include improved collaboration, better risk management, and enhanced overall system quality. These benefits provide a compelling reason to adopt MBSE.
- **Comfort**: Assess what is keeping the organization from making the step forward. Comfort zones often include familiar processes, tools, and workflows that stakeholders are accustomed to. This inertia can be a significant barrier to change. Understanding these comfort factors is crucial for developing strategies to encourage stakeholders to adopt MBSE.
- **Fears**: Identify the fears and concerns that are pushing back or blocking the adoption of MBSE. These may include apprehensions about the complexity of MBSE, potential disruptions to current workflows, and uncertainties about the return on investment. Addressing these fears through clear communication, training, and demonstrating early wins can help mitigate resistance and build confidence in the new approach.

By systematically understanding addressing these “PGCF” aspects, a structured and supportive environment can be created for introducing MBSE. Such a change management approach ensures that the transition can be managed effectively. With a clear focus on the main cost and time drivers, this leads to a smoother and more successful deployments.

9.2.6 HOW to start?

When introducing Model-Based Systems Engineering (MBSE) into an organization, it is essential to follow a structured approach that focuses on methodology first, then language, and finally tools. Tools are only enablers, not the drivers towards relieving pains nor the drivers to enabling gains. Furthermore, when introducing MBSE, begin with (smaller) pilot projects before deploying MBSE more widely across the organization.

When introducing MBSE in an organisation, the following steps are advisable:

1. **First Select Process, then Methodology, then Tool/Notation**: Start by defining the processes and methodologies that will be used. Once these are established, select the appropriate tools and notations that align with the chosen methodologies. Provide comprehensive training to ensure that all team members understand how to use these tools effectively.
2. **Ensure Access to Tools and All Resulting Artefacts**: Make sure that all stakeholders have access to the necessary tools and the artefacts produced during the MBSE process. This ensures transparency and facilitates collaboration.
3. **Start Small, Continuously Validate, Increase Scope Slowly**: Begin with small pilot projects to test and validate the MBSE approach. Use these initial projects to gather feedback, make adjustments, and demonstrate the value of MBSE. Gradually increase the scope of MBSE applications as confidence and experience grow.
4. **Communicate Results in Ways All Stakeholders Understand**: It is crucial to communicate the results and benefits of MBSE in a manner that is understandable to all stakeholders: this may require different communication paths! Use clear and concise language and tailor the communication to the audience's level of expertise and interest.
5. **Learn and Adopt; Suggest Changes to Business Processes**: Continuously learn from the MBSE implementation process and be open to adopting new practices. Suggest changes to existing business processes based on the insights gained from MBSE to improve overall efficiency and effectiveness.

The caveat with these steps is to regularly check the stakeholders and the Pain-Gain-Comfort-Fear (PGCF) matrix, as organizations are dynamic and change over time. Reviewing the stakeholder inventory and the PGCF matrix regularly helps to ensure that all relevant stakeholders are still engaged, and their concerns still are addressed. This helps in maintaining alignment and support throughout the MBSE deployment process.

9.2.7 Deployment strategy

Deploying MBSE is a lengthy process that requires significant upfront investment. Successful MBSE deployment depends heavily on effective stakeholder engagement. This involves identifying all stakeholders, assessing their position in the adoption cycle and tailoring communication to address their concerns. It is important to focus on areas where MBSE can demonstrate early wins and to be realistic about what MBSE can and cannot address. Clear communication, continuous learning, and regular reviews are crucial to maintaining alignment and support throughout the implementation process.

The following are crucial elements in a deployment strategy, based on lessons learned at Ford Automotive [62]:

- **Vision and Planning.** Define a high-level vision for MBSE deployment, including key pain points, value propositions, and a flexible plan to achieve the vision. This vision should be agile enough to adapt to changing circumstances while maintaining strategic direction. A clear roadmap helps guide decision-making and prioritisation throughout the deployment journey.

- **Senior-Level Support.** Secure support from senior leadership, such as vice presidents or general managers, to champion the MBSE initiative. Leadership endorsement provides credibility and facilitates resource allocation. It also helps overcome resistance and ensures alignment with broader organisational goals.
- **Budget and Team Building.** Identify budget streams, responsible owners, prioritisation processes, and key calendar dates to engage stakeholders. Build a diverse and enthusiastic team by networking across the organisation and involving individuals from different departments. This diversity enhances the relevance and resilience of the deployment strategy.
- **Stakeholder Mapping.** Identify key stakeholders and influencers who can support or must adopt the MBSE vision. Develop strategies to engage positive stakeholders and manage those who may be resistant. Understanding stakeholder dynamics is essential for effective communication and adoption.
- **Multi-Level Engagement.** Create a multi-level engagement plan to educate various organisational layers and influencers. Tailor educational content to different audiences, ensuring relevance and clarity. This approach helps build a shared understanding and supports consistent deployment across teams.
- **Value Proposition Communication.** Communicate the MBSE vision widely, highlighting organisation-specific value propositions. Use internal networks to identify pain points and align MBSE benefits with day-to-day business needs. Effective messaging strengthens stakeholder commitment and supports sustained engagement.
- **Training and Information Management**. Develop a detailed plan for phased training in process, methodology, tool, and information management. Ensure that training is practical, role-specific, and aligned with deployment goals. This builds competence and confidence in MBSE practices across the organisation.
- **Vendor Engagement.** Partner with key MBSE solution tool vendors to ensure alignment and support. Engage vendors with a vested interest in the deployment's success or hire experts to work alongside internal teams. This collaboration enhances tool integration and accelerates capability development.

By communicating clear and realistic expectations and fostering a collaborative environment, organisations can approach MBSE deployment with greater confidence. A structured and well-planned approach, supported by leadership and continuous learning, enables early successes and lays the groundwork for lasting improvements in an organisation's systems engineering practice.

9.3 Questions and challenges discussed with industry

How to ensure successful MBSE deployment was a recurrent theme during the entire MBSE phase 2 study. In this workshop, industry partners shared a wide range of questions and challenges as well. The discussions revealed recurring themes that reflect both strategic and operational concerns.

Discussions were organized around the following themes: i) Vision, Value and Strategic Alignment, ii) Stakeholder Engagement and Organisational Buy-in, iii) Scaling and Organisational Complexity, iv) Governance and Ownership, and v) Tooling, Integration and Technical Enablement. Below sections provide brief summaries of these discussion topics.

9.3.1 Vision, Value and Strategic Alignment

A clear and shared vision is essential for successful MBSE deployment. Workshop participants emphasised the importance of aligning MBSE efforts with business objectives, identifying key pain points, and defining a flexible roadmap that supports phased implementation.

Key discussion points and challenges were the following:

- Organisations emphasised the importance of articulating a clear MBSE vision, identifying key pain points, and defining a flexible roadmap. This includes identifying strategic goals, a 'north star,' aligning the MBSE roadmap with business objectives, and ensuring that this vision resonates across departments. Such a strategic clarity helps guide prioritisation and ensures a focus on value. A phased approach, starting e.g. with feature-driven MBSE and evolving towards integrated modelling and simulation, exemplifies this principle.
- How can the value of MBSE deployment be estimated and prioritised? Estimating the value of MBSE deployment remains a challenge [11] [12], particularly in complex environments with diverse stakeholders. Participants noted the need to balance ambition with feasibility, using pilot projects to demonstrate early value. Identifying and addressing an organisation's pain points in an agile fashion can help to build momentum and offers a concrete way to show value to the business and secure support.
- What does a fit-for-purpose approach to systems engineering look like? Achieving systems engineering effectiveness and value demands tailoring MBSE practices to organisational context and complexity. Examples included the use of reference architectures to support consistent value delivery. Participants highlighted the importance of balancing standardisation with flexibility to accommodate evolving needs.

Strategic alignment with business objectives is a prerequisite for success of MBSE deployment. By defining a clear vision, estimating value pragmatically, and addressing pain points, organisations can build a roadmap that supports both short-term value and long-term transformation. The insights shared in this theme highlight the importance of adaptability, stakeholder engagement, and continuous refinement.

9.3.2 Stakeholder Engagement and Organisational Buy-in

Stakeholder engagement emerged as a recurring theme in the workshop discussions. Introducing MBSE into an organisation is a process of change that touches many layers of the organisation. Participants emphasised the importance of building organisational support for MBSE deployment, not just through formal endorsement but also by fostering shared understanding and commitment across teams.

Key discussion points and challenges were the following:

- Engaging the community and motivating teams to adopt MBSE practices is a persistent challenge. How can organisations identify relevant actors early and understand their position in the adoption cycle? Participants stressed the importance of internal champions and cross-functional collaboration but noted that these efforts require tailored communication strategies to build trust and relevance. As noted in the workshop, 'How to engage the community, get people going?' remains a central concern. Who dares to take the leap of faith?

- Creating structural support for MBSE principles requires both leadership endorsement and grassroots involvement. What mechanisms can help align MBSE goals with departmental priorities to ensure relevance across the organisation? Participants pointed out that multi-level engagement and education plans are needed to reach the involved organisational layers, but such plans are often difficult to sustain.
- Working effectively with teams and organisations involves building shared understanding and technical alignment. How can modelling methodologies be clarified in a way that supports collaboration and does not disrupt existing R&D structures? Participants suggested that starting with an agile modelling approach can facilitate iterative development and reduce resistance. Still, the challenge remains in balancing flexibility with the need for consistency and traceability across teams.
- Communicating complex MBSE solutions in an accessible way remains a challenge. How can organisations tailor messaging to different audiences and make MBSE concepts relatable? Organisations must tailor messaging to different audiences and use examples that are both understandable and considered relevant, hence must be carefully chosen to resonate with specific groups.
- Inspiring vision is particularly important for engaging younger professionals. What kind of narrative can motivate participation and foster innovation among emerging talent? Participants observed that agile modelling and digital thread concepts tend to resonate with younger engineers, who often seek clarity and purpose in their work. The challenge is to connect these ideas to concrete opportunities within the organisation.
- Communicating the MBSE vision and organisation-specific value propositions helps build commitment. Participants noted that aligning MBSE benefits with day-to-day business needs is a way to 'connect MBSE to business value' without overselling or oversimplifying impact. Identifying pain points and tailoring messaging accordingly requires ongoing effort and feedback to be effective.

In summary, stakeholder engagement is an integral part of MBSE introduction. It requires ongoing attention to organisational dynamics, communication, and alignment. The workshop underscored that MBSE is as much about people and processes as it is about models and methods. Building trust, fostering dialogue, and maintaining relevance across teams are key ingredients for a sustainable MBSE journey.

9.3.3 Scaling and Organisational Complexity

Scaling MBSE across an organisation involves navigating existing organisational structures, managing interdependencies, and maintaining clarity of purpose. Participants discussed how organisational complexity—across disciplines, departments, and sites—can challenge the consistency and relevance of MBSE practices.

Key discussion points and challenges were the following:

- How can MBSE be scaled without losing sight of its intended goals? Scaling MBSE practices without compromise of deployment goals requires careful planning and coordination. Organisations must ensure that MBSE initiatives complement existing processes rather than disrupt them. Agile planning and alignment with existing PLM structures and tools can help keeping the transition manageable.

- Managing complexity across disciplines, departments, sites, and stakeholders is a core MBSE challenge. MBSE must operate across multiple domains, each with its own language and practices. Reference architectures and shared ontologies were seen as helpful ways to support integration across engineering disciplines. Still, coordination mechanisms are needed, and the question remains how to maintain coherence without over-standardising or losing flexibility.
- Embedding MBSE in the organisation requires alignment with existing structures and processes. Embedding MBSE is not only a technical task—it requires integration with business workflows and decision-making. The challenge is to ensure that MBSE does not become isolated from the broader organisational context.
- How can organisations address skill gaps and prepare teams for MBSE? Succes of MBSE deployment depends on the availability of appropriate skills across the organisation. Participants discussed the importance of phased training plans that cater to various levels of expertise: awareness, practitioner, and expert. Team-based modelling approaches were suggested to support learning in context. The challenge is to balance formal training with hands-on experience and consultancy support.
- Transitioning to MBSE is not a linear process. Participants emphasised the need for flexible planning, probing, and iterative steps to adjust to new insights. Managing emergence—where new insights and needs arise during the transition—was seen as essential part of the journey. The challenge is to maintain direction to a 'north star' vision, while allowing room for adaptation and learning.

Scaling MBSE in large organisations is complex. Widening the team and usage beyond the initial group of 'believers' necessitates aligning structures, building skills, and managing change in a way that fits the organisation's rhythm, all while maintaining coherence and consistency. The workshop discussions underscored that MBSE must be embedded thoughtfully, with attention to both engineering and organisational realities.

9.3.4 Governance and Ownership

Governance and ownership emerged as important themes in relation to MBSE deployment and organisational embedding. Participants shared that clarity in roles, responsibilities, and approval processes is essential to maintain consistency and avoid confusion. The challenges discussed underline the need for structured collaboration and transparent decision-making.

Key discussion points and challenges were the following:

- Defining ownership during transition and deployment is a recurring challenge. Who is responsible for what, and how is this communicated across teams? Unclear roles can slow down progress and reduce accountability, especially when modelling activities span multiple departments. Clarifying who owns what in the modelling process helps prevent duplication and misalignment. Some organisations addressed this by developing modelling plans that specify responsibilities and encourage shared ownership.
- Establishing ownership of model elements is essential for consistency and traceability. How can organisations ensure that model content is maintained and approved in a structured way? Without clear responsibilities, teams may struggle to coordinate efforts or validate model content. Approval and configuration processes must be transparent and scalable. Participants noted the importance of governance structures that include approval workflows and version control. Examples included configuration modelling and repository management practices that support disciplined collaboration.

- Model governance and assurance require both technical and organisational mechanisms. What structures can support regular review and feedback across stakeholders? Participants discussed the value of stakeholder loops and review cycles to maintain model quality, and helping to keep assurance aligned with business priorities.

Overall, governance and ownership in MBSE deployment are not just about assigning tasks—they are about creating a shared framework for collaboration and decision-making. The discussions showed that clarity, transparency, and structured processes are key to maintaining momentum and ensuring that MBSE efforts are sustainable across teams and departments.

9.3.5 Tooling, Integration and Technical Enablement

Tooling and integration were discussed as enablers, but also as sources of friction in MBSE deployment. Participants reflected on the need to balance technical possibilities with organisational realities, and to ensure that tools support—not drive—the engineering process.

Key discussion points and challenges were the following:

- Balancing tool support with expert involvement is a key concern. How can organisations ensure that tools enhance rather than replace engineering judgement? Participants noted that while tools offer structure and automation, they can also lead to over-reliance and reduce critical thinking. Several organisations addressed this by embedding experienced engineers in modelling teams, maintaining expert judgement and interpretation alongside tool use.
- Connecting MBSE models to software development environments, especially in agile contexts, remains challenging. What are effective ways to bridge the gap between system models and software development workflows? Participants shared that integration with platforms like GitHub and Jira helped manage model packages but also required careful coordination. The challenge lies in maintaining coherence between evolving models and iterative code development, especially when teams operate at different speeds.
- Managing model interfaces at both logical and technology levels requires structured modelling. How can organisations maintain consistent interface definitions across models, tools, and teams? Using shared architectures and service-oriented modelling approaches helped some teams maintain interface clarity and reduce friction across disciplines and domains.
- Ensuring model production viability and repository integration involves human and technical processes. What criteria should be used to determine when a model is ready for inclusion in shared repositories? Participants emphasised the importance of validation steps and clear workflows for repository management. Establishing a model management process and involving multiple stakeholders helps ensure that models are not only technically sound but also useful and accepted in the broader organisation.

Tooling and model integration shape how teams collaborate and how decisions are made. The workshop discussions suggested that thoughtful integration, combined with clear roles and shared understanding, can help organisations make MBSE work in practice.

9.4 Workshop Observations and Conclusions

This fourth workshop focused on the organisational embedding of MBSE and the practical realities of introducing MBSE across diverse teams and settings. Discussions revealed that the challenges of MBSE deployment are primarily rooted in Systems Engineering itself—its purpose, strategy, and organisational alignment—rather than in tooling or methodology. Participants repeatedly emphasised that MBSE is merely a means to improve how Systems Engineering is practiced. In this, and prior workshops too, many of the discussions centred on SE-related concerns, with MBSE positioned as a supporting framework to address them more effectively.

9.4.1 Workshop Observations

Building on the broader reflections of the fourth workshop, this section captures specific observations from participants regarding the organisational realities of MBSE deployment. Rather than focusing on tools or methods, the discussions centred on how MBSE interacts with existing systems engineering practices, organisational structures, and stakeholder dynamics.

The following observations summarize key themes and practical insights shared that emerged during the workshop discussions.

- **No one size fits all.** Participants consistently noted that MBSE adoption cannot follow a single blueprint. Organisational context, product complexity, and existing engineering practices all influence what works and what does not. This means that each organisation must find its own balance between structure and flexibility, and between ambition and feasibility.
- **Understand the business need and create a multi-level engagement plan.** A recurring theme was the importance of linking MBSE efforts to concrete business needs. This raises the question: how can MBSE initiatives be positioned to support both strategic goals and day-to-day operations? Participants stressed the value of engagement plans that address different layers of the organisation, from engineering teams to senior management.
- **MBSE is foremost a change management activity**. Rather than being a purely technical shift, MBSE introduces new ways of working that affect roles, responsibilities, and expectations. How can organisations manage this transition without overwhelming teams or losing momentum? Several participants described the need to grow while maturing, and to move from early adopters to broader organisational uptake.
- **Multiple MBSE roles are emerging.** As MBSE practices evolve, so do the roles involved. Participants mentioned roles such as Subject Matter Expert, Modeler, Model User, and Model Information User. This raises the challenge of how to connect these roles effectively, especially between modelers and business or system stakeholders.
- **Organise training and MBSE method/profile/tool support.** Training was seen as essential to support adoption, but also as something that must be tailored. How can organisations provide training that meets people where they are? Participants suggested structuring training around awareness, practitioner, and expert levels, supported by appropriate methods and tools.
- **Consider model assurance: when is a model trustworthy?** Trust in models is not automatic—it must be earned through quality assurance and governance. What criteria should be used to assess whether a model is ready for use? Participants discussed the role of QA metrics, model governance, and regular review cycles.
- **Outside perspectives help.** Bringing in external speakers was seen as a valuable way to broaden the discussion. How can lessons from other domains be used to inform local MBSE practices? Examples and deployment experiences from other sectors helped participants reflect on their own approaches.

- **MBSE** – DO's and DON'Ts. Participants shared a range of practical insights based on their experiences. These insights (in line with ESA views [61]) included both positive practices and common pitfalls, see Table 2.

Table 2 - Considerations for MBSE introduction.

Increase chance of success	Reduce risk of failure
○ Develop a clear plan covering both initial and ongoing costs (including licences, infrastructure, maintenance, and training). Secure sponsorship. ○ Ensure long-term availability and stability of models, modelling tools and repositories to safeguard MBSE investments. ○ When tailoring MBSE methods and tools to fit business processes, favour lightweight approaches to ease adoption. ○ Exploit the power of digital artefacts from the outset; apply automated checks to enforce compliance and consistency. ○ Establish an accessible internal MBSE community that meets regularly to share insights and foster engagement.	○ Keep the focus: maintain continuous alignment between modelling efforts and the business problem being addressed. ○ Adjust MBSE practices to suit stakeholders with varying maturity levels and adoption paces; adapt to their evolving objectives. ○ Limit too early mixing of methods and tools, while recognising the need for multiple model types. ○ Guard against low commitment (too many fallback plans and parallel activities). Ensure early planning and front-loading activities. ○ Ensure the best possible MBSE experience: reliable tool access and strong tool performance; seamless integration with ICT and security.

These observations underline the importance of aligning MBSE efforts with organisational realities. While technical enablers such as tools and methods play a role, the workshop made clear that successful MBSE deployment hinges on strategic engagement, role clarity, and building trust in model-based practices. The insights shared offer practical guidance for managing the transition from early experimentation to broader organisational adoption.

9.4.2 Conclusions

The fourth workshop highlighted that embedding MBSE within an organisation is foremost a change management activity. Success depends not only on technical readiness but on the organisation's ability to **grow while maturing**—moving from a small group of "believers" to broader adoption across teams and departments. Participants emphasized the importance of taking the organisation along, with structured engagement and clear communication at all levels.

Multiple MBSE roles are emerging, including Subject Matter Experts (SMEs), Modelers, Model Users, and Model Information Users. Connecting these roles—particularly modelers to business and system stakeholders—requires deliberate planning and support. Training must be organised across awareness, foundation, and practitioner levels, tailored to the needs and maturity of distinct groups.

Model assurance was identified as a critical enabler for trust and adoption. Questions such as "when is a model trustworthy?" must be addressed through robust model QA, governance, and metrics. Without this, models risk being sidelined rather than serving as authoritative sources of engineering truth.

The workshop reinforced that MBSE must be introduced as part of a broader organisational transformation. This includes managing expectations, aligning with business needs, and building internal communities that sustain momentum. Only with the right strategy, MBSE can grow from a specialised practice to a broadly embedded capability that strengthens systems engineering across an organisation.

10 Observations, Recommendations and Next steps

10.1 Introduction

Model-Based Systems Engineering (MBSE) continues to gain traction as a strategic enabler for improving systems engineering (SE) effectiveness in the high-tech equipment industry. The second phase of the MBSE study, conducted by TNO-ESI in collaboration with its industrial and academic partners, focused on deepening the understanding of MBSE's practical value, deployment challenges, and organisational implications. This phase built on the foundational insights from the first study, which had already identified MBSE as a promising approach for managing complexity, improving traceability, and fostering interdisciplinary collaboration.

The study was structured around four thematic workshops, each addressing a key topic identified during phase 1: interface management, variants and diversity, critical-to-quality (CTQ) and system behaviour, and organisational embedding of MBSE. These workshops brought together practitioners from various partners and external speakers to share experiences, explore dilemmas, and identify actionable strategies. In addition to the workshops, deep-dive sessions and pilot project reviews provided further insight into how MBSE is being applied across different organisational contexts.

A recurring theme throughout the study was the recognition that MBSE is not a plug-and-play solution. Its successful deployment requires a fit-for-purpose strategy that aligns with the organisation's maturity, business drivers, and engineering culture. MBSE must be embedded within existing SE practices and adapted to the realities of brownfield development, legacy systems, and evolving product platforms. It must also support the full lifecycle of systems—from concept to disposal—while enabling collaboration across departments, disciplines, and external partners.

The study also highlighted the importance of organisational readiness. MBSE introduces new roles, responsibilities, and ways of working. It requires investment in training, governance, and stakeholder engagement. Without these, MBSE risks becoming a niche activity with limited impact. Conversely, when introduced strategically and supported by leadership, MBSE can become a key capability that strengthens systems engineering across the organisation.

Finally, it is important to recognize that MBSE is not a substitute for technical leadership nor for sound system architecting. While MBSE provides powerful methods and tools to 'design the product right' (by supporting engineering processes, consistency, and traceability), success in the market also depends on 'designing the right product.' This requires a deep understanding of business needs, market context, technological trends, the competitive landscape, and translating these into a coherent product strategy and fit-for-purpose architecture. Ultimately, MBSE should be seen as an enabler that strengthens both dimensions: supporting rigorous engineering execution while ensuring that business and architectural choices remain aligned with strategic objectives and customer value.

This section summarises the key observations and recommendations from the study, based on the collective insights of the participating organisations. It sets the stage for the next steps, which will focus on consolidating lessons learned, advancing applied research, and supporting the broader adoption of MBSE in the high-tech equipment industry.

10.2 Observations and Recommendations

The second phase of the MBSE study revealed a consistent pattern across workshops, interviews, and pilot reviews: successful MBSE deployment in the high-tech equipment industry depends on organisational readiness, strategic alignment, and a clear understanding of the business context.

This context is characterised by complex, low-volume systems, where the emphasis lies more on technical leadership and customer-specific innovation than on lifecycle optimisation. TNO-ESI partners predominantly operate in this domain, using MBSE to support engineering excellence and tailored solutions. The following observations and recommendations are therefore framed within this context of complex, customer-specific system development.

10.2.1 Interface-Centric MBSE as a Pragmatic Entry Point

Observation. Interface management consistently emerged as a low-risk, high-impact starting point for MBSE adoption. As outlined in Section 6.2, modelling interfaces provides immediate value in distributed and brownfield development environments, where integration issues often arise at component boundaries. By formalising interfaces, organisations can clarify responsibilities, reduce ambiguity, and mitigate costly redesigns. The workshop findings reinforced that even modelling a single critical interface—especially when used as a contractual artefact with suppliers—can yield tangible benefits and foster cross-organisational alignment.

Recommendation. Organisations should initiate MBSE deployment by focusing on interface modelling. This approach delivers early value without requiring a full system model and helps build confidence in model-based practices. Establishing governance mechanisms for interface classification and evolution supports modularity and long-term maintainability. As discussed in Section 6.3, treating interfaces as formal control points enables better cross-functional collaboration and lays the groundwork for broader MBSE adoption, including integration with Product Line Engineering and system architecture modelling.

10.2.2 Variation Management and Product Line Engineering

Observation. Managing product diversity and platform-based development remains a central challenge in the high-tech equipment industry. As discussed in Section 7.1, the shift toward composable platforms and configure-to-order strategies introduces significant complexity, particularly in low-volume, high-variability environments. Without structured modelling approaches, organisations risk inconsistent product definitions, fragmented reuse, and uncontrolled variation. Workshop findings confirmed that many organisations struggle to balance flexibility with control when developing and maintaining product families.

Recommendation. The emergence of SysML v2 significantly enhances the ability to model variability and support Product Line Engineering [33]. Its improved semantics and modular constructs enable systematic reuse, configuration logic, and impact analysis across product lines. As highlighted in Section 7.2, model-based support for architectural modularity and platform strategies is essential to manage complexity and maintain consistency. Organisations should invest in modelling strategies that align with business priorities, reduce lifecycle costs, and support customer-specific innovation. Integration of MBSE with PLM and sales configurators can further strengthen responsiveness to evolving market needs.

10.2.3 Critical-to-Quality (CTQ) Modelling and System Behaviour

Observation. Critical-to-Quality (CTQ) properties—such as performance, reliability, and safety—are essential for meeting customer expectations and contractual obligations. However, as highlighted in Section 8.1, many organisations are still in the early stages of integrating analytical modelling and simulation into their MBSE practices. The first focus remains on descriptive models, which limits the ability to reason about CTQs, perform trade-off analyses, and support virtual system development. Workshop discussions emphasised the importance of connecting descriptive and analytical models to enable early validation and informed decision-making.

Recommendation. Organisations should expand MBSE practices to include analytical modelling capabilities that support CTQ reasoning throughout the development lifecycle [54]. As discussed in Section 8.2, tools such as ModelCenter [41] and connector standards like FMI [42] and Comet [43] can facilitate integration between descriptive system models and domain-specific analyses. This enables continuous verification, impact analysis, and early validation of CTQs. Structured interdisciplinary collaboration is essential to build modelling competence and ensure that CTQ modelling becomes a core element of engineering practice.

10.2.4 Embedding MBSE in Organisational Practice

Observation. Embedding MBSE into organisational practice is not merely a technical rollout—it is a complex change management effort. As discussed in Section 9, successful deployment requires alignment across multiple dimensions: organisational structure, roles and responsibilities, capability development, and governance. The study revealed that many organisations face challenges in defining clear MBSE roadmaps, establishing ownership, and integrating MBSE into existing engineering and business processes. Without a coherent embedding strategy, MBSE risks remaining a niche activity with limited organisational impact.

Recommendation. A phased and business-aligned deployment strategy is essential. Organisations should begin with targeted pilot projects that address concrete business challenges and demonstrate value. These pilots should be used to refine MBSE-related roles and to establish model assurance processes that ensure quality and consistency.

Embedding MBSE also requires structured capability development. Training should be differentiated across awareness, foundation, and practitioner levels, tailored to the needs of different stakeholder groups. Internal communities of practice can support knowledge sharing and sustain momentum. As emphasised in Section 9.3, leadership sponsorship and clear communication of MBSE's strategic value are critical to overcoming resistance and fostering long-term adoption.

10.2.5 Interdisciplinary and Ecosystem Collaboration

Observation. MBSE must extend beyond systems engineering to support collaboration across disciplines and organisational boundaries. As discussed in Section 8.3, effective model-based collaboration requires models that are understandable and usable by a wide range of stakeholders, including suppliers, service teams, and domain experts. However, ecosystem-wide adoption is often constrained by tool incompatibilities, fragmented workflows, and the absence of shared standards for model exchange and interpretation.

Recommendation. Organisations should invest in interdisciplinary modelling strategies and adopt connector standards to facilitate model exchange across the value chain. As highlighted in Section 8.4, MBSE methods must support bi-directional information flow and be tailored to stakeholder concerns, enabling meaningful participation from all disciplines. Strengthening interoperability and shared modelling practices is essential to unlock the full potential of MBSE across the engineering ecosystem.

10.2.6 Agile Compatibility and Incremental Adoption

Observation. The high-tech equipment industry is increasingly adopting agile and concurrent engineering practices such as SAFe [63]. As discussed in Section 7.3, MBSE approaches are sometimes perceived as rigid and misaligned with the pace of iterative development. The study emphasised the importance of aligning MBSE with agile principles to avoid over-formalisation and to support responsiveness in fast-moving environments [64] [65].

Recommendation. MBSE should be introduced through agile-compatible methods, focusing on lightweight modelling and incremental validation. Pilot projects should target high-leverage areas such as e.g. interface modelling (see Section 10.2.1) to demonstrate early value. Organisations should avoid premature standardisation and instead allow MBSE practices to evolve organically, guided by business needs and stakeholder feedback. This approach supports flexible and iterative evolution and fosters broader acceptance across engineering teams.

10.3 Next Steps

Following the completion of this MBSE study, the initiative continues in the form of a Special Interest Group (SIG). This SIG will provide a platform for ongoing knowledge exchange, peer learning, and exploration of emerging MBSE practices, albeit with a reduced effort and a focus on half-day sessions centred around specific topics.

The SIG is designed to support systems engineers working in the high-tech equipment industry and who are advancing MBSE within their organisations. The SIG is intended for systems engineers in the high-tech equipment industry who are actively engaged in advancing MBSE within their organisations. Its ambition is to deepen the collective understanding of MBSE's value across TNO-ESI partners, and together explore the conditions required for successful adoption in complex, low-volume system development.

Based on the interests of the participants, the SIG will address several open themes identified during the study, including the following:

- Model integration & governance.
- Interface management and change impact.
- Traditional SE versus MBSE.
- Value and success of MBSE initiatives, how to quantify?

The SIG will also serve as a forum to share experiences from pilot projects, discuss tooling developments and approaches to adapt modelling approaches in response to evolving business needs. Participation is open to all TNO-ESI partners and, on invitation, related interested stakeholders committed to advancing MBSE in the high-tech equipment domain.

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