MBSE in the High-Tech Equipment Industry

MBSE-Study of ESI and Partners - Observations and Conclusions

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1 Introduction

In 2020, ESI was approached by several of their industry partners with questions about Model-Based Systems Engineering (MBSE). 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-based methodologies to address Systems Engineering challenges. After doing a quick literature scan, ESI took the initiative to start an *MBSE-study* in close cooperation with their industry and academic partners in June 2020.

After introducing the study to their partners, a team was formed with representatives from:

- Industry partners:
  - ASML
  - Canon Production Printing
  - Philips
  - Thermo Fisher Scientific
  - Thales
  - Vanderlande[1]
- Academic partners
  - Delft University of Technology
  - Radboud University
  - University of Twente
- TNO
  - ESI (TNO)
  - other units in TNO.[2]

The study ran until December 2021.

After giving an overview of the structure of the study, this report describes the main observations, conclusions and recommendations (per December 2021). For 2022, a continuation of the study has been proposed, which will be briefly introduced in the final section of this report.

Results from the study have been shared in presentations at the MBSE-webinar organized by ESI in October 2020 [1], in the MBSE Applied Webinar [2, 3] in IDEW'21 (webinar week organized by ESI in April 2021) and during the Capella Days 2020 [4].

ESI wishes to thank their partners and the MSBE method and tool suppliers who contributed to the results of this study.

[1] Vanderlande was not part of the partner board of ESI in 2020 and 2021. In the TouchBase and RunBase projects of ESI (TNO) and Vanderlande, MBSE was a topic of research. Therefore, Vanderlande was invited to participate in the MBSE-study together with the other partners of ESI. In 2020, Vanderlande decided to join the ESI-partner board per January 1, 2022.

[2] Representatives of the System Engineering Guild of TNO joined the study in 2021.

2 Study Overview

2.1 Study Charter

The MBSE-study was started in 2020 based on the following observations:

- The industry partners of ESI are exploring the feasibility and value of Model-Based Systems Engineering (MBSE). Several partners are conducting small-scale pilots, some partners are even doing their proof-of-concept applications at a somewhat larger scale.
- In the network of ESI, several definitions of "MBSE" were being used, creating confusion and misalignment.
- MBSE-methods and tools are maturing, but their adoption is still rather low in the high-tech equipment industry. In specific domains, MBSE is becoming a mainstream approach (primarily in defense and aerospace, and to some extent in automobile), in other industries the adoption of MBSE is much slower.

ESI and its partners concluded that a joined effort should be formed to explore the feasibility and added value of MBSE in the high-tech equipment industry.

One of the specific aspects to be considered was: how to align both the competencies and the research program of ESI (TNO) to (i) optimally leverage the capabilities of MBSE, (ii) focus on those areas where innovations of MBSE-methodologies are needed for optimal embedding of MBSE in the high-tech equipment industry.

The charter mentioned the following ambition for the study:

We want to
- enable successful[3] embedding of applicable MBSE-methods and tools in the high-tech, software-intensive equipment industry (characterized by the industry partners of ESI);
- optimize the research roadmap of ESI (i) to leverage available MBSE-methods and tools in future projects and (ii) to focus on those areas of MBSE-related research that would contribute to successful embedding of MBSE

and therefore, we need:
- to understand the ambitions and motivation of the industry to invest in embedding MBSE in their industry processes[4];
- to understand the state-of-the-art/practice of MBSE-methods and tools;
- to understand the capabilities, industrial adoption and roadmaps of leading MBSE-tools.

[3] Where "successful" stands for embedding of MBSE in such a way that there is clear economical added value of MBSE for the industry.

[4] Before jumping into MBSE-methods and tools, we wanted to understand the industrial challenges and opportunities related to the introduction of MBSE: (i) to understand the current status of systems engineering and modelling in the high-tech equipment industry and (ii) to understand the difference between the way models are used in today's industrial systems engineering and MBSE.

In the MBSE-study we worked on all three items. In this report, we summary our understandings in all three areas: industrial motivation, state-of-the art methods and tools, the capabilities of leading MBSE-tools.

2.2 Study Structure

The MBSE-study was performed in three phases:

- Phase 1: exploration of **drivers and ambitions** for introducing MBSE
  In a series of workshops, the focus has been on the industry partners: what are their motivations to explore the added value of MBSE? Where do they expect MBSE to have added value? Which challenges and opportunities do they want to address with MBSE?

  After these workshops, ESI created an overview of the industry landscape for MBSE: the drivers and motivations were mapped on a 2x2-matrix to indicate that different drivers are likely to require different features from the MBSE-methods/tools. An overview of these results can be found in section 4 of this report.

- Phase 2: exploration of **contemporary MBSE-methods** and tools
  To get a better understanding of contemporary MBSE-methods and tools, ESI studied literature on MBSE (during and before the study). In addition to this, leading MBSE-vendors were approached to setup a series of meetings to present and discuss the capabilities of their methods and tools. An overview of the results can be found in section 5 of this report.

- Phase 3a: visits to **industry pilots** (of the partners)
  As several industry partners were already applying MBSE-techniques at some scale (as pilots or as first proofs of concepts), all industry partners were invited to show their work. A series of visits[5] was organized in which the industry partners shared their approach, status and results with the other partners. As parts of these presentations contained confidential information that cannot be disclosed beyond the parties that have signed the NDA, a full account of these sessions cannot be given. A short overview is provided in section 6.

- Phase 3b: visits to **academic research projects** on MBSE.
  With the academic partners represented in the study, we discussed whether they were doing any MBSE-research themselves that could serve as input and inspiration for the study. From these discussions, we concluded that there are no running MBSE-research projects at these universities at this moment. It is clear that programs are running on Systems Engineering methodologies and that modeling plays an important role in these. These programs do not specifically target MBSE, however (as defined in section 3).

This report gives an overview of the observations and conclusions from these three phases and gives a perspective on next steps.

[5] In view of restrictions to travelling and group meetings in 2020 and 2021 due to the COVID19-pandemic, these “visits” were virtual visits using virtual meeting platforms. During the pandemic, we learned to exploit the capabilities of such platforms and to have lively and interactive sessions despite the virtual nature of our meetings.

Note: in parallel to the MBSE-study, ESI (TNO) and their partners have been performing various applied research projects addressing MBSE, e.g., the TouchBase and RunBase projects at Vanderlande in which platform-based R&D and Configure-to-Order approaches were explored using MBSE-techniques (using Enterprise Architect in particular) [5], the PaloAlto2-project at Thermo Fisher Scientific in which Reference Architecting was explored, using MBSE-techniques for the modeling (using Arcadia/Capella in particular) [6, 7, 8] and the Canvas project at Canon Production Printing in which Reference Architecting was studied and in which a MBSE-tool study was performed. Lessons-learned from these parallel projects have also been consolidated in this report.

2.3 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:

Alberto Fazzi	Philips	**Harm Kooiker**	Philips	**Marcin Gramza**	Thermo Fisher Scientific
Alexandr Dubielczyk	Philips	**Harry Kuipers**	Philips	**Martijn Riemeijer**	Thermo Fisher Scientific
Anne van Lievenoogen	Philips	**Jacco Wesselius**	ESI (TNO)	**Michael Kubis**	ASML
Arjen Klomp	Thermo Fisher Scientific	**Jamie Mc Cormack**	Thermo Fisher Scientific	**Olivier Rainaut**	Thermo Fisher Scientific
Daniel Strüber	Radboud University	**Jelena Marincic**	ESI (TNO)	**Patric Wender**	Philips
Erik Teesink	Philips	**John van der Koijk**	Philips	**Paul Harvey**	Philips
Fatih Erkan	Vanderlande	**Jonnro Erasmus**	ASML	**Rentia Barnard**	ASML
Frances Brazier	Delft University of Tech.	**Joost Dierkse**	Thermo Fisher Scientific	**Richard Doornbos**	ESI (TNO)
Frank Benders	TNO	**Joris van den Aker**	ESI (TNO)	**Rik Jansen**	TNO
Frank de Lange	ASML	**Louis Stroucken**	Philips	**Roelof Hamberg**	Canon Production Printing
Frank Schuurmans	ASML	**Luc Casterman**	Philips	**Teun Hendriks**	ESI (TNO)
Frank van den Berk	Vanderlande	**Ludger van der Laan**	TNO	**Thomas le Montagner**	Thales
Freek Molkenboer	TNO	**Maarten Bonnema**	University of Twente	**Timon van Slooten**	Thales
Harald Keicher	Canon Production Printing	**Marc Verdiessen**	ASML	**Vaclav Prajzner**	Thermo Fisher Scientific
				Wouter Tabingh Suermondt	ESI (TNO)

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

3 MBSE and Models in Systems Engineering

To get the study started, we focused on defining "MBSE". In a short exploration preceding the MBSE-study, ESI conducted a literature survey and starting from a common definition of Systems Engineering, a working definition for MBSE was shaped.

3.1 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 [9]

Systems Engineering is an engineering discipline that has emerged from the space and defense industry. It focusses on the multi-disciplinary, system-level approach to successfully realize, use and retire systems. The INCOSE definition quoted above (taken from [9]) addresses the specific aspects of systems engineering in detail. Another, less detailed, description found in the SEBoK [10] 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*.

In the Systems Engineering Handbook of NASA [11], this is explained 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, behavior, 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 cross-disciplinary, 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 [11]). Systems[6] engineering concentrates on the design

[6] 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 [41].

and application of "the whole" as distinct from the parts.

At 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.

3.2 Model-Based Systems Engineering

Model-based systems engineering was kicked off by INCOSE by its MBSE Initiative in January 2007 [12]. INCOSE considers MBSE part of a long-term trend towards model-centric approaches throughout development and later life cycle phases [13]. 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 analyzing 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 a well-defined formalism, and they form the consistent single engineering truth.

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

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

A general concept in MBSE is that the models are the authoritative[7] 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.

3.3 MBSE ≠ SE with Models

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?

[7] 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.

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 "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, the documents were the authoritative source of information. We noticed many occasions, where documents, including the modeling 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 single purpose: the 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. A 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.

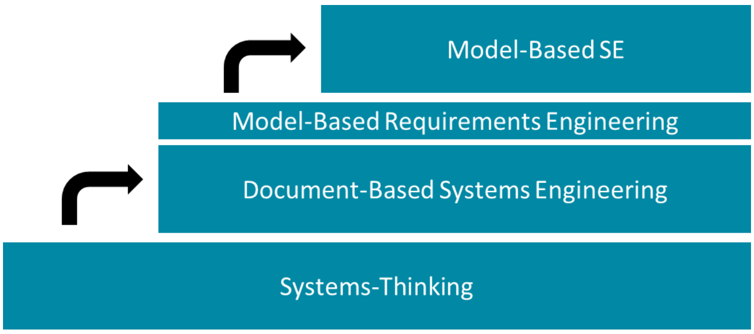

Figure 1 - MBSE builds on SE and Systems Thinking

3.4 Business Cases for MBSE

In those companies in which MBSE has been adopted, positive results have been reported. An overview of these results can be found in a Sandia report [14]. The report refers to a well-known result from a study by Carnegie Mellon University [15]. This study indicates the beneficial effects of Systems Engineering in general. As indicated in Figure 2, teams with high SE Capabilities typically perform better than teams with low/middle SE Capabilities. In this report, "Higher SEC" means that SE is not just applied for requirements but throughout the entire System Development Life Cycle (SDLC). The Sandia-report claims that similar observations would apply for Model-Based SE: major benefits can only be expected when MBSE is applied throughout the entire SDLC and not just for requirements engineering.

The positive effects of applying MBSE is also reported in the 2015 MBSE Survey of Stevens Institute of Technology [16]. Participants confirm the high value of MBSE (although the presentation also rightfully indicates that the survey is biased).

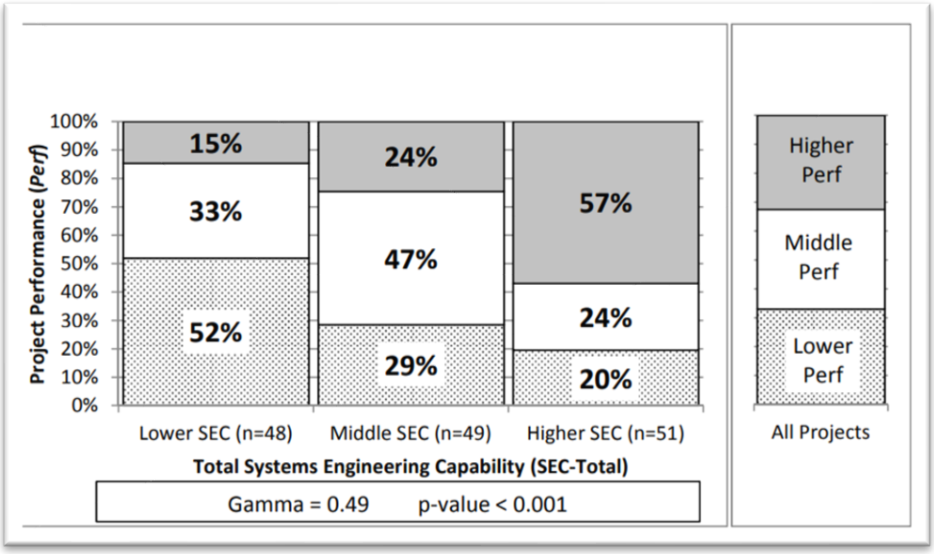

Figure 2 - Project Performance vs. Total SE Capability (from [15]) – teams with high SE capabilities perform better

The Sandia report also refers to a publication of Tomassi and Vacca [17, p. 15] (based on a survey conducted by EMF - Embedded Market Forecasters in 2013: MBSE gives a major benefit over traditional document-based systems engineering in terms of (i) projects delivered on time, (ii) reduction of development cost per project. Another report of EMF gives information about the impact of MBSE in the period 2013 – 2015: “Between 2010 and 2015, MBSE developments show a distinct advantage over similar projects that don’t use MBSE. […] The data supports the idea that while the average cost of all systems developments have improved over the period 2010-2015, MBSE developments have not only proved to be less costly (roughly less than half as costly) but have continued to cost less as experience with MBSE has increased. ” [18, p. 6]

In general, reports indicate major cost savings and quality improvements when model-based engineering practices are introduced. Similar cost savings are reported by Gooden in [19] (see Figure 3). A report from NDIA [20] gives an overview of the areas in which these benefits are expected to be found. They sketch the system development life cycle and indicate the MBSE-opportunities per life cycle phase (see Figure 4).

Based on a series of cases, the Sandia-report [14, pp. 31-44] summarizes the benefits of MBSE (justifying the investments) based on the fact that avoiding late changes to requirements and finding defects as early as possible. They also emphasize that these benefits are lost when MBSE is only used for requirements engineering, benefits, MBSE should cover the entire SDLC. In those cases where MBSE is well-applied over the entire SDLC, the investment in MBSE has a positive Return on Investment according to the findings reported by Sandia.

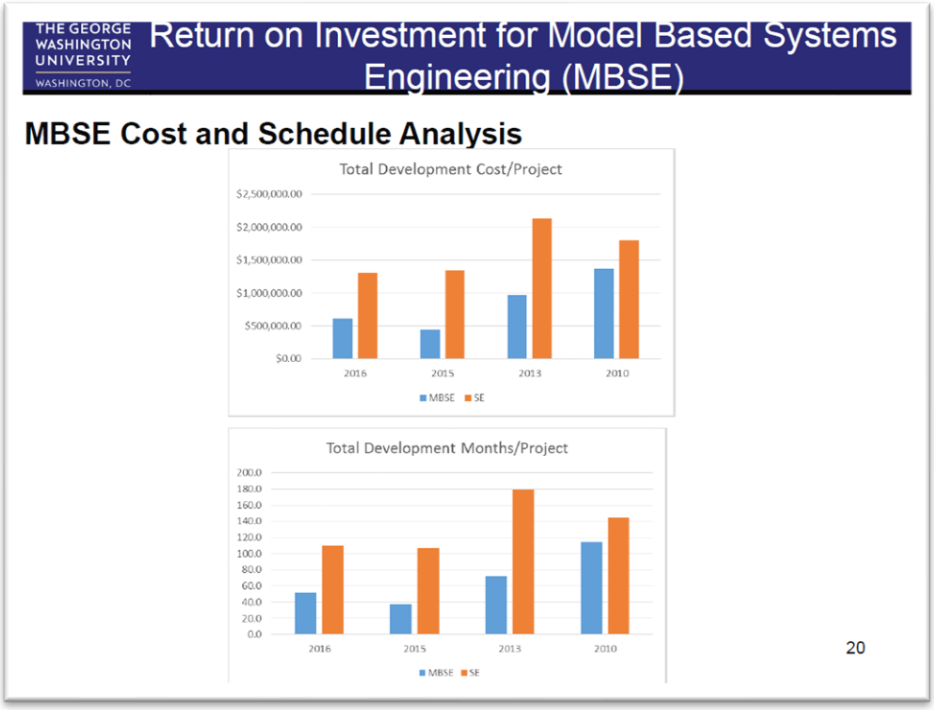

Figure 3 - Cost benefit analysis: MBSE costs (blue bars) vs SE costs (orange bars (from [19, p. 20])

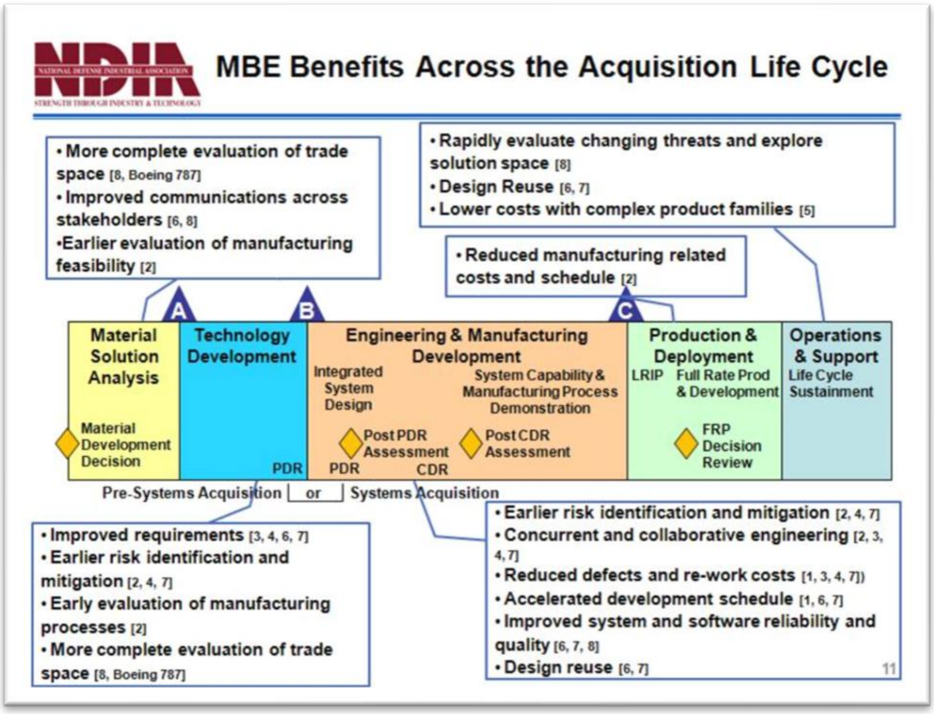

Figure 4 - MBSE benefits across the life cycle (from [20, p. 16])

The Sandia-report [14] also indicates prerequisites for successful introduction of MBSE:

- mature, well-documented, and enterprise-wide SE processes that span the SDLC;
- trained systems engineers in MBSE techniques;
- access to training in the SE processes for all engineers;
- defined processes for model management throughout the SDLC;
- investment in full-scale MBSE tools.

In addition to these, the following commitments are needed from the organization:

- to initiate modeling with appropriate staffing levels at the beginning of the program;
- to perform configuration management for the model “first change the model, the model is the design”;
- to provide continuous resources to maintain the models throughout the SDLC;
- to provide MBSE resources and models to support system testing, qualification, and V&V;
- to provide appropriate sustained computing infrastructure throughout the SDLC.

The cases studied by Sandia indicate that those organizations that have the basic preconditions in place get major benefits from applying Systems Engineering in general and an MBSE approach in general [14, p. 8]. Before jumping into MBSE, organizations should reflect on their competencies and management commitments: do they meet the prerequisites as given above?

A final remark to the industry experiences referred to in this section is that there is a strong bias to a specific industry: aerospace and defense (in particular in the US). For our study, we are targeting a different category: commercial, high-tech equipment manufacturers. The business context for this category of industries is different (as will be discussed in sections to follow). As a consequence, the role and value of Systems Engineering, and Model-Based Systems Engineering in particular, is likely to be different (see also the description of the industry drivers for MBSE in the next section). The MBSE experiences described in the reports referred to in this section can therefore not be applied one-on-one to the industrial partners of ESI, but they still form a strong foundation for their interest in MBSE. Reaching out to MBSE users in the aerospace and defense industry to exchange experiences is therefore at the agenda of the MBSE-study of ESI and partners (exchange with SERC is ongoing, and a first exchange with companies in their network happened during the IDEW’21 webinar on *MBSE Applied* [2] where presentations were given by MBSE practitioners from a wide range of industries).

4 Drivers for MBSE-Adoption

As explained in the Introduction, we started our study with a series of workshops to discuss the motivation of our industry partners to embark on introducing MBSE in their organizations. With questionnaires and follow-up discussions, we were able to sketch the landscape for our industry partners:

- ASML (https://www.asml.com/en)
- Canon Production Printing (https://cpp.canon/)
- Philips (https://www.philips.com/global)[8]
- Thermo Fisher Scientific (https://www.thermofisher.com/nl/en/home.html)[9]
- Thales (https://www.thalesgroup.com/en)[10]
- Vanderlande (https://www.vanderlande.com/)

During our discussions, we observed that different companies use different words to express their motivation for MBSE. We noticed that their motivations were similar in many aspects, but that there were many specific aspects in them as well. To avoid getting a very fragmented view on the motivations for MBSE we looked for a simple structure to map the individual motivations. Inspired by the work of Quinn and Cameron on cultural typology [21, 22] and the color coding of Insights Discovery [23], we chose to apply a matrix with four quadrants, where each quadrant captures a class of drivers for MBSE (drivers that seem to be closely connected to the cultures and business strategies in the companies).

The four quadrants (see Figure 5) are created by combining two axes:

- Does the motivation for introducing MBSE stem from an internal driver (internal efficiency drive) or from an external driver (customer and market orientation, interaction with (new) external sources)?
- Does the motivation stem from a need to be in control and to optimize efficiency or from a need to be more flexible?

This gives us four quadrants (that seem to correspond to the culture typology of Quinn and Cameron):

1. **Collaborate** **[Internal | Flexible]**
   In this quadrant we see motivators for MBSE such as:
   - having multiple, independent teams of engineers doing concurrent engineering (and the need to assure that their design deliverables integrate into a product);
   - the need to spread knowledge about the system through-out the organization;
   - the desire to enhance collaboration across disciplines in self-managing teams.

2. **Create and Explore** **[External | Flexible]**

[8] Specifically: Philips Image Guided Therapy (Best, The Netherlands), Philips MR (Best, The Netherlands) and the Systems Engineering Competence Center (Eindhoven, The Netherlands)
[9] Specifically: Transmission Electron Microscopy (Eindhoven, The Netherlands and Brno Czech Republic)
[10] Specifically: Thales Nederland (Hengelo, The Netherlands)

In this quadrant we see motivators for MBSE such as:

- being able to explore new design options and to simulate their consequences (at system level);
- being able to perform trade-space analysis and to make trade-off decisions taking the system-wide scope of the impact of design choices into account.

3. **Predictable [Internal | Control]**

In this quadrant we see motivators for MBSE such as:

- assuring that all requirements are met and verified;
- standardizing the way of working throughout the organization.

4. **Effective and Efficient [External | Control]**

In this quadrant we see motivators for MBSE such as:

- being able to quickly compose customer specific systems/solutions from platforms of pre-designed and pre-released components (see for instance the public presentation from Vanderlande on this topic during the MBSE-webinar of ESI [24];
- reduce the time from taking an order to delivering a system to the customer (configure-to-order and efficient verification and release of system variants);
- being able to assure the properties (qualities) of system configurations (especially when systems are shipped in a large number of diverse configurations/variants).

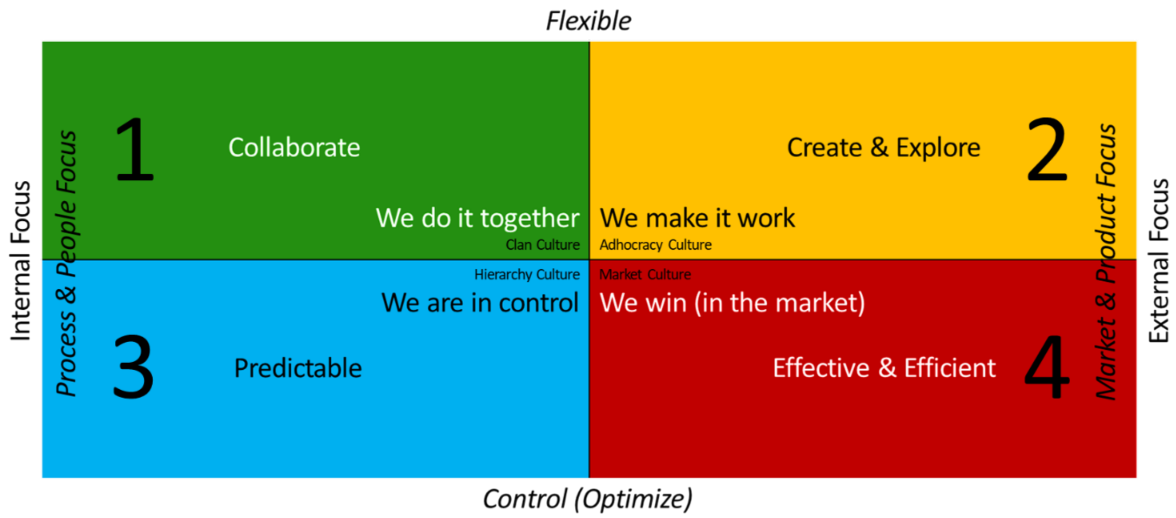

Figure 5 - Quadrants to map motivations for MBSE-introduction (inspired by Quinn and Cameron [22, 21] and Insights Discovery [23])

During the workshops, we identified the main drivers for our partners to explore the introduction of MBSE. Without giving the details of the individual companies involved, we can give an indication of the main motivators identified in the study (plotted on the four quadrants in Figure 6)[11]:

- quadrant 1: enhancing cooperation and knowledge exchange;
- quadrant 1: consolidating knowledge from legacy systems for a new generation of engineers;

[11] It is, of course, a simplification that drivers can be placed in a single quadrant; there is always a mix of drivers from multiple quadrants. Meeting the requirements and expectations related to drives from multiple quadrants is an additional complication of introducing MBSE. In the workshops that led to the overview in Figure 6, we asked all industry partners to identify their primary and secondary drivers and we performed a weighted count.

- quadrant 4: leveraging platforms to accelerate system/solution design and delivery;
- quadrant 4: assuring the properties/qualities of system variants shipped to customers.

All partners expect the core benefits of MBSE: the authoritative, consistent, and easily accessible system-wide information. To them, this is the enabler that MBSE is expected to provide for the desired outcome.

Please note that quadrant 2 (create and explore) scored signigicantly lower. This could create the impression that our partners would not be interested in using models to speed up innovation and to create better products and services. This conclusion would be incorrect: they already use models for this purpose, that is not the added-value they expect from the introduction of MBSE; these (engineering) models are typically not connected and they do not establish the “authoritative source of truth”. They do, however, expect MBSE to enable smoother communication and knowledge exchange about those innovations, which is part of the drivers in quadrant 1.

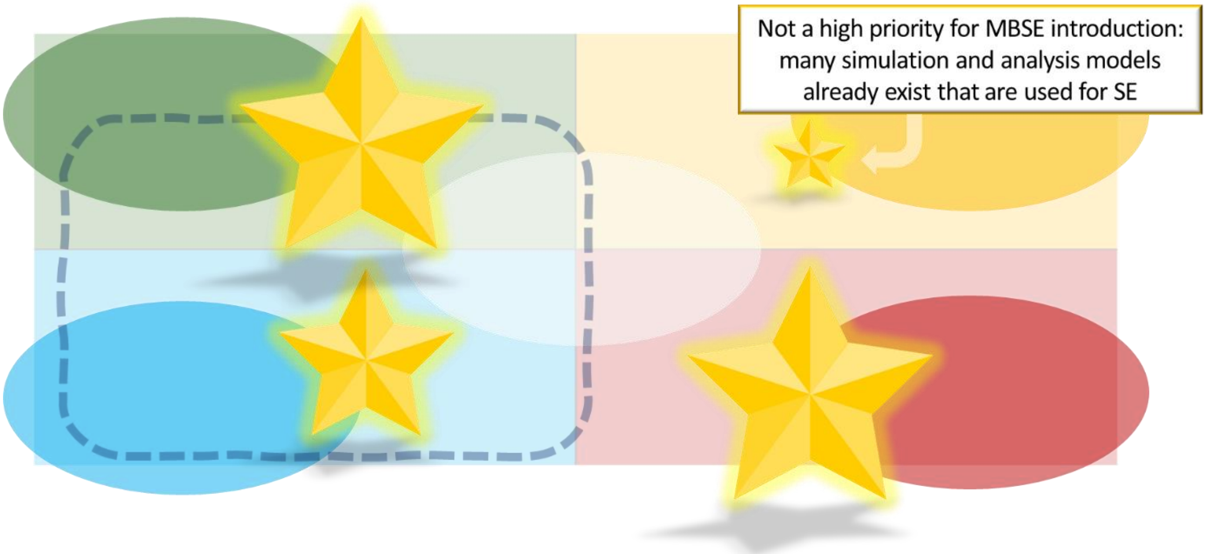

Figure 6 - The Main MBSE-motivators from the industry partners in our study

Greenfield versus Brownfield

An important observation during the project is related to the business context of our industry partners. When we discussed the introduction of MBSE with our partners at the Systems Engineering Research Center (SERC, https://sercuarc.org/), they explained that the defense projects in which MBSE is applied can typically be called “green field”: a new piece of military equipment is being designed “from scratch”. This is completely different in the industrial context of our partners; they typically innovate in a *brown field* context. Their business context can be characterized by: (i) this year’s system is an incremental, evolutionary innovation of last year’s system and (ii) a large portion of their business is directly related to legacy systems in their installed base and therefore (iii) a large portion of their R&D capacity is used to sustain their installed base, including the delivery of upgrades to 15 systems that are 15 years old.

The brown field nature of our partners' business context gives them specific challenges that also drive their motivations for exploring MBSE:

- As they have to efficiently and effectively sustain their installed base for long periods of time (typically 20-30 years), they have teams that are knowledgeable of those systems. Developing the system-level domain knowledge for new engineers requires a lot of time and a steep learning curve. Therefore, consolidating systems engineering knowledge of legacy systems and making it easily accessible to a new generation of engineers is crucial for their business. This is clearly a motivator for quadrant 1.
- As they have delivered systems in a wide range of configurations and generations, consolidating the knowledge required to sustain the installed base is complex. MBSE is hoped to bring an innovative way to structure the required systems engineering information and to assure consistency. Note, however, that often information is available about the *as-shipped* status of systems, but that information about the *as-in-operation* status is often lacking. This enhances the challenges for sustaining the installed base dramatically. Also here, models and digitalization (getting field data etc.) are hoped to help.
- As next year's system is in most cases an evolutionary innovation from this year's system, in-depth knowledge about this year's system is crucial for successful innovation. This also puts a strong focus on knowledge consolidation and knowledge exchange.

What complicates the introduction of MBSE in such organizations is the fact that there are no authoritative models for current and past systems. Instead of models, large sets of documents have been created that typically are neither fully up to date, nor fully consistent. Next to the documents, knowledge is typically captured in organization and processes, databases, people (the experienced "local heroes"), etc. Introducing MBSE requires leap-frogging this chasm. MBSE cannot be introduced in a clean-sheet manner and a complex transition path is needed in which hybrid approaches (document-based and model-based systems engineering) will be needed.

"We'll start the war from right here"

(General Theodore Roosevelt jr., D-day, Utah Beach [25])

When discussing this challenge with Michael Vinarcik[12] of ASIC during the preparation of his presentation at IDEW'21 [26], Michael advised us to follow General Theodore Roosevelt III when the conditions for a smooth, top-down introduction of MBSE are not set: find opportunities where modeling can create immediate benefit for the systems engineers and their organization, start from where you have landed – start the war from right here.

In section 6 - Industry Pilots – we will briefly discuss the MBSE pilots and proof of concept projects of our industry partners. What we will see is that they have taken a similar approach: finding specific challenges for which MBSE can have immediate return on investment and start from there to proof the value of MBSE in their industry contexts.

[12] https://www.linkedin.com/in/michaelvinarcik/

5 Contemporary MBSE Methods and Tools

5.1 Positioning MBSE on the Industry MBSE-Motivators

As part of the MBSE-study, we explored the capabilities and strategies of contemporary MBSE-methods and tools. Our observation is that these tools typically focus on quadrant 3 (Predictable and Control, as sketched in Figure 7 on page 19) by providing SysML-alike modeling languages and tools. In this area all tools provide techniques to create an RFLP-alike[13] structure: Requirements are captured and mapped on functions; Functions are decomposed into Logical units and finally mapped on Physical units implementing it. In this quadrant, MBSE-tools primarily offer techniques for function decomposition and allocation. As many systems engineering considerations are strongly linked to these qualities, this is clearly an area where new methods, tools and techniques are needed. This point has been recognized and currently at OMG, a taskforce is working on a next generation SysML V2 [27] which will address these issues.

In addition, several tools provide advanced collaboration environments supporting distributed teams (quadrant 1). In this quadrant, we did not find methods and tools that actively support processes to deal with the complications of working in a brownfield (as discussed in *Greenfield versus Brownfield* on page 16). In this quadrant we miss methods, tools and techniques to capture and share knowledge of legacy and current systems. Often, having the design itself is not enough; knowing the design rational or intent is needed to make optimal decisions for design changes and future designs. In quadrant 1, methodologies to address this are crucial, especially for companies dealing with evolutionary innovation and with legacy systems that contribute significantly to their brown-field business.

Don't the models obscure the rationales and intents?

(Several Systems Architects at the start of the study)

At the start of the MBSE-study, we conducted a series of meetings with the partners invited for the study. In these meetings, we introduced the study and its charter, and we asked the invited partners: "what are your main ambitions and concerns regarding the introduction of MBSE in your organization?"

The main ambitions and motivations have been summarized in section 4 of this report. One of the concerns mentioned by several of the architects was: how do the models help me to convey the design rationale and intent?

They were concerned that the models might even obscure the design rationales and intents. If the models are assumed to be the authoritative source of systems engineering information, they should also capture and convey those rationales. Can models be used for this? Today, the architects spend a lot of their time talking with design teams to convey the rationales and intents. Do we expect models to reduce the role the talking? If not, how can the models ever become the authoritative source of information?

[13] R = Requirements, F = Functions, L = Logical Decomposition, P = Physical Decomposition

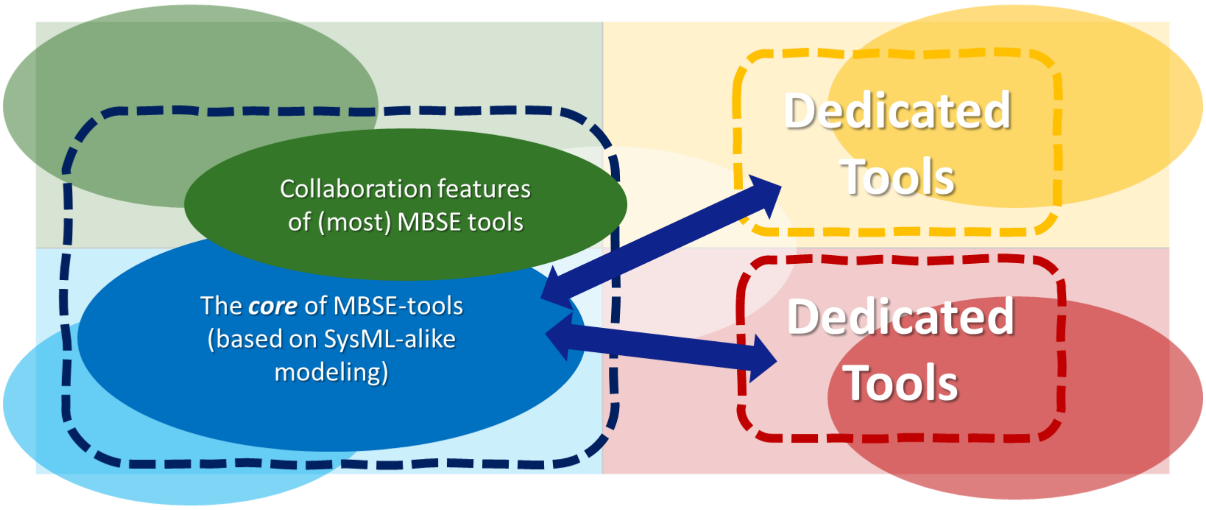

Figure 7 - The MBSE landscape mapped on the four quadrants

Finally, we concluded that the quadrants 2 and 4 are somewhat outside the scope of "core MBSE": SysML modelling (or methods using SysML-alike formalisms). We noticed that several MBSE vendors have the strategy to deliver full tool suites, including PLM (quadrant 4) and analysis/simulation tools (quadrant 2). Others focus on the MBSE-core functionality and have the strategy to connect to dedicated PLM, simulation and analysis tools through the open interfaces provided by these. We noticed that also those vendors that aim to develop a full tool suite are creating open interfaces to create networks of multi-vendor tools. In section 5.5, we will give a high-level overview of our observations and conclusions from a tour along the main MBSE-tool vendors.

From our analysis, we concluded that:

- The MBSE-core functionality (SysML-alike modeling and RFLP-decomposition) forms the foundation to create the expected benefits for our industry partners, but this is somewhat limited to functional modeling/decomposition and to creating an authoritative source of truth for those aspects. This is a good start to meet the MBSE-motivations in quadrant 3.
- Our industry partners need more added value from the introduction of MBSE:
    - They need a platform for model-based collaboration and concurrent engineering. We noticed that most contemporary tool suites provide functions for this, where one tool will be more advanced than another tool.

    - They need methods, tools and techniques to collect and share knowledge about systems in their installed based and about systems in development. We noticed that the available MBSE tool suites do not focus on this aspect. They do provide functionality to model system variants/diversity (in some cases with support of third-party extensions to their tools) but creating these models can be rather cumbersome.

What we have not seen at all, are methods and tools to create models from legacy design artefacts (e.g., documents, Excel sheets, Visio diagrams, CAD files) to bootstrap MBSE in a brown-field environment.
We also have not seen methods and tools for knowledge modeling and sharing to capture and share design intent and rational.

- They need tools to support platform-based (configure-to-order-alike) system/solution design: composing customer-specific solutions from platforms of building blocks. This aspect is not part of the MBSE-core, but other tools are available to support such processes. Interfaces are being created to bridge the gaps between the MBSE-core methods and tools and such dedicated tools.

  Given the MBSE-motivations of our industry partners, integrating key aspects of platform-thinking into the MBSE-core methods and tools is called for.

- Likewise, modeling is a key aspect of the design exploration and analysis in quadrant 2. Our partners need strong interfaces between simulation and analysis tools and the MBSE-core tools to assure that the combination of the SysML-alike models and the simulation/analysis models constitutes a consistent, authoritative source of systems engineering information to support the collaboration and concurrent engineering characterizing their MBSE-motivation in quadrant 1. Simulation can also play an important role to create quantitative models of system qualities. We have seen that integrations with simulation tools are possible with the leading MBSE methods/tools.

5.2 MBSE in the System Life Cycle

As discussed in the previous subsection, the MBSE-core only covers a part of the industry motivators for introducing MBSE. In Figure 8, we have sketched this in a different way: the MBSE-core focusses on functional decomposition; it tries to pave the path from requirements to the allocation of functions on physical units. These physical units can then be connected to building blocks in PLM-systems. What we miss is a clear focus on non-functional aspects and system qualities. We consider that a problem, as the non-functional aspects drive most of the key architecture decisions.

For some non-functionals, a decomposition process can suffice, e.g., when a system budget can be split into budgets for subsystems as could be the case for properties such as cost of the bill of materials or system weight. For many system qualities, the so-called *emerging properties*, such approach does not work well as these properties are typically emergent properties that are created by complex interactions between components. A well-known example is the “flying” qualities of an airplane: none of the components has the property itself, one cannot give a “flying budget” to individual subsystems and decompose the property that way; to evaluate if a design has the “flying property”, several components need to be combined that together make the thing fly.

As sketched in Figure 8, in those cases we often see that:

- A link is made to more detailed design and development activities for relevant subsystems;
- simulation and analysis tools are used to evaluate the system's qualities, or multi-physics modelling is performed to assess such properties;
- the results from these simulations are used as feedback to improve the overall system design or to improve the detailed engineering diagrams.

Although the leading MBSE-tools do provide interfaces to tools for creating detailed engineering designs and for simulation and multi-physics modeling, a well-defined process to deal with non-functionals/system qualities lacks from contemporary MBSE-methods/tools. This limits their applicability and added-value, as the MBSE-models to not constitute a complete system view and therefore cannot be the authoritative source of systems engineering information.

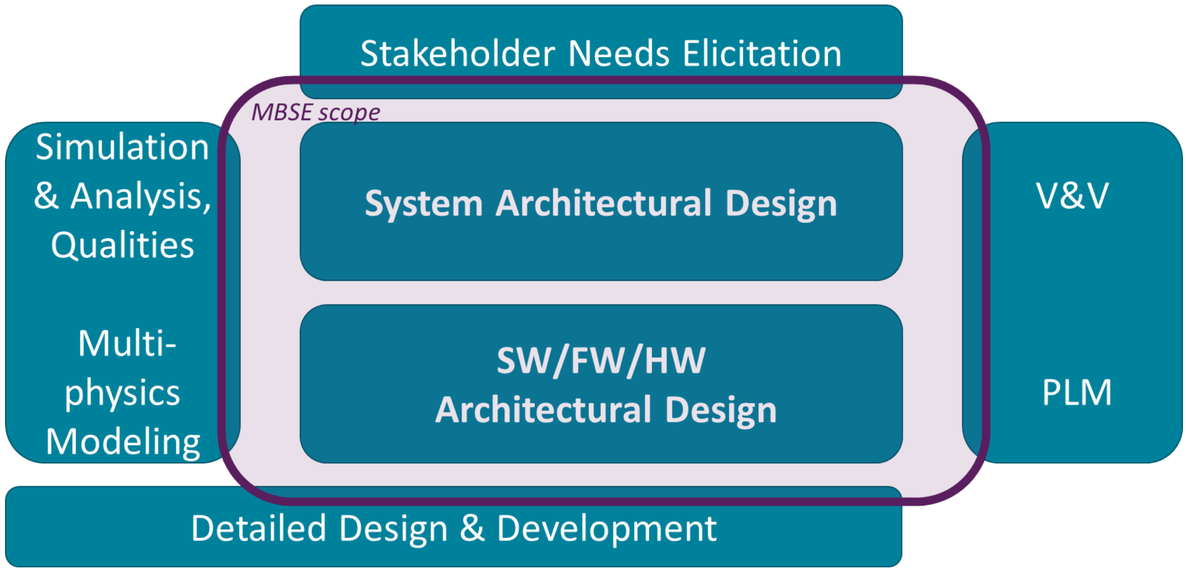

Figure 8 - MBSE in a larger process scope

When considering the full product development life cycle and all the models that would be needed to constitute the complete authoritative source of systems engineering information (e.g., by using a V-model as sketched in Figure 9, which gives an indication of the range of models that would be needed), it is clear that solely a set of RFLP-models will not be sufficient; a multitude of models will be needed to cover a variety of system aspects, for a variety of audiences, at various levels of details). To replace the humongous document sets created for complex systems, large and complex (connected sets of) models will be needed.

Creating an authoritative source of systems engineering information goes far beyond the creation of the initial MBSE-models. Even though these models can certainly help to structure systems engineering information and to make it accessible to a large group of stakeholders, many additional models and stakeholder-specific views[14] are needed to capture all relevant system aspects and stakeholder concerns. The models need to be handed over to people from different disciplines like manufacturing, service, purchasing etc. Since today's complex high-tech equipment is typically

[14] SysML is not the optimal language for communication with all stakeholders in an organization. Stakeholder-specific views, using a language fitting their background and concerns, are called for.

realized in complex value chains involving many companies, to streamline the full chain, models need to be handed over between companies too[15]; companies that can have different model-based practices in place. Exchange of systems engineering information among engineering disciplines, stakeholders and value chain partners via models is expected to be challenging.

In addition, the initial models will have to be maintained and they will evolve over time as market requirements change and new technology insights emerge. Managing changing models and determining the impact of changes (for new systems as well as for legacy systems in the field) will be a challenge, as it is today with unstructured information. Hopefully models will help to reduce the maintenance challenge of systems engineering information. For ESI, this is a key area of future research: how to create and manage such sets of systems engineering models?

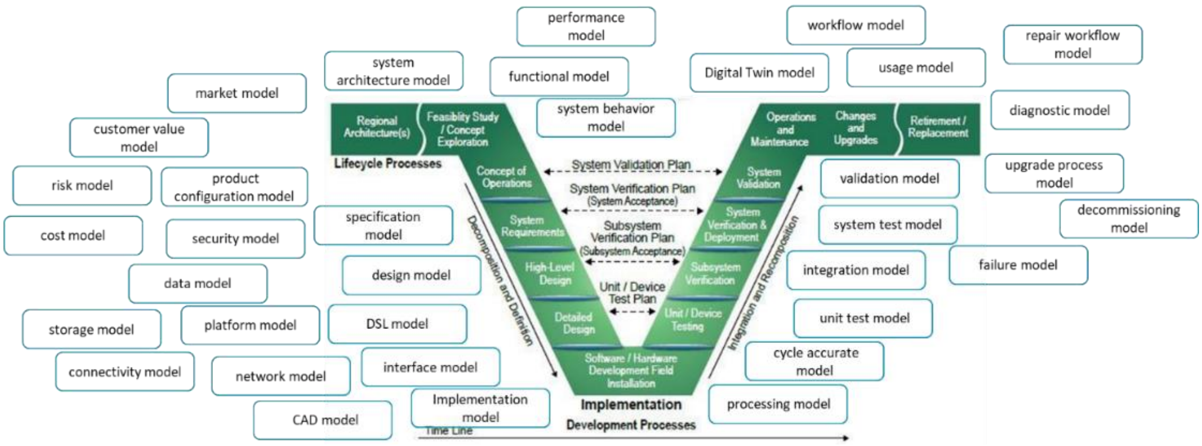

Figure 9 - Systems Engineering Models across the System Life Cycle

5.3 Systems Engineering and the other disciplines

A final comment on the application of contemporary MBSE-methods and tools is linked to the discussion above: how to connect the Systems Engineering models to the other disciplines such as software engineering, electronics engineering, mechanical engineering, mechatronics, metrology, logistics, optics, manufacturing, service, etc.? Typically, these disciplines will provide the detailed engineering diagrams (see Figure 8) needed for simulation, hardware in the loop, digital twinning, test rigs etc. used to evaluate emergent system properties.

We have encountered situations like the one sketched in Figure 10: Systems Engineers create systems models (using MBSE-methods and tools), and other technical disciplines create their own types of models. Also, for special aspects such as reliability, safety, security, etc., dedicated models are created by experts. Often islands of models are created without well-established “bridges”.

The consequence of this is that models created by the systems engineers only cover some top-level (RFLP-alike) system aspects. Some of the key properties (the “specialties”) are not well addressed in these models, nor are system aspects addressed by specific engineering disciplines . If e.g., software control determines important aspects of system behavior, then a link between system and software

[15] A specific aspect to be considered is: how to assure that company knowledge is not leaked when models are exchanged? It might be needed to create dedicated view for value chain partners (e.g., suppliers and design partners) that only contain the information they need to have to make their contributions, shielding confidential IP.

models is needed. This holds too for hardware architectural choices that have a large impact at systems level – the engineering diagrams, as discussed in the previous section.

A key concern to be addressed when moving into MBSE is: how to assure that a connected and consistent set of models can be created across the disciplines that can truly be the (single) authoritative source of truth for all systems engineering information for everybody, over the full life cycle of the system? We conclude that this is still a challenge for contemporary MBSE-methods and tools, that has not yet been resolved in practical implementations of MBSE.

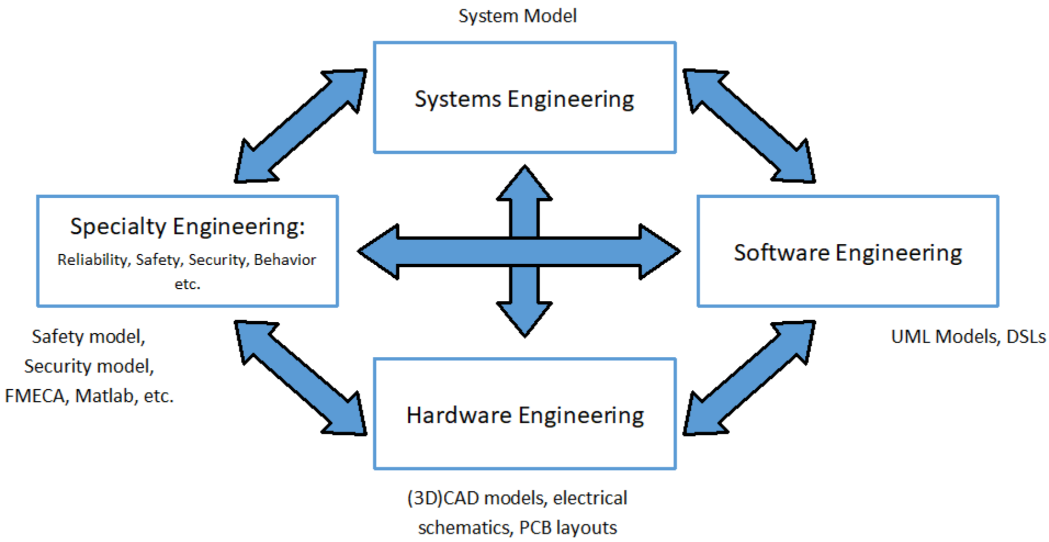

Figure 10 - Engineering Model Islands (with bridges?)

5.4 MBSE and the Digital Engineering Goals

Digital Engineering is a broadening of Model-Based Systems Engineering initiated by the US Defense industry to manage its complex systems projects (Digital Engineering Strategy [28]). The US Department of Defense (DoD) defines Digital Engineering as “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”.

Digital engineering shall comprise “[a systems engineering] approach to securely and safely connect people, processes, data and capabilities across an end-to-end digital enterprise”. The observed challenge is that “the current bureaucratic approach, centered on exacting thoroughness and minimizing risk above all else, is proving to be increasingly unresponsive” [29].

DoD’s Digital Engineering strategy defines 5 top-level goals (see also Figure 11) to achieve a transition to “a culture of performance where results and accountability matter” as follows [29]:

1. *Formalize the development, integration and use of models to inform enterprise and program decision making.*
2. *Provide an enduring, authoritative source of truth.*
3. *Incorporate technological innovation to improve the engineering practice.*
4. *Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders.*

5. *Transform the culture and workforce to adopt and support digital engineering across the lifecycle.*

For each of these 5 goals a number of focus areas are given. For goal 2 (Provide an enduring, authoritative source of truth), for instance, the focus areas are i) plan and develop the authoritative source of truth, ii) Govern the authoritative source of truth, and iii) Use the authoritative source of truth across the lifecycle.

From these goals and focus areas it is clear that a successful transition to Digital Engineering requires significant advances on many areas, i.e., in methods, processes, tools, technology, data, people (and culture), as indicated in Figure 12.

Figure 11 - Digital Engineering Goals and focus areas (from [30])

To create this "continuum across disciplines to support lifecycle activities from concept through disposal" [28], besides the introduction of tools and methods, a lot of attention effort needs to be expended on the creation of organizational capabilities. Planning and governance are important, but also training the workforce and transforming the culture, as well as building up (and capturing) knowledge require a concerted effort. To achieve the full benefits from digitizing systems engineering, *just introducing MBSE tools and the associated methods will not suffice.*

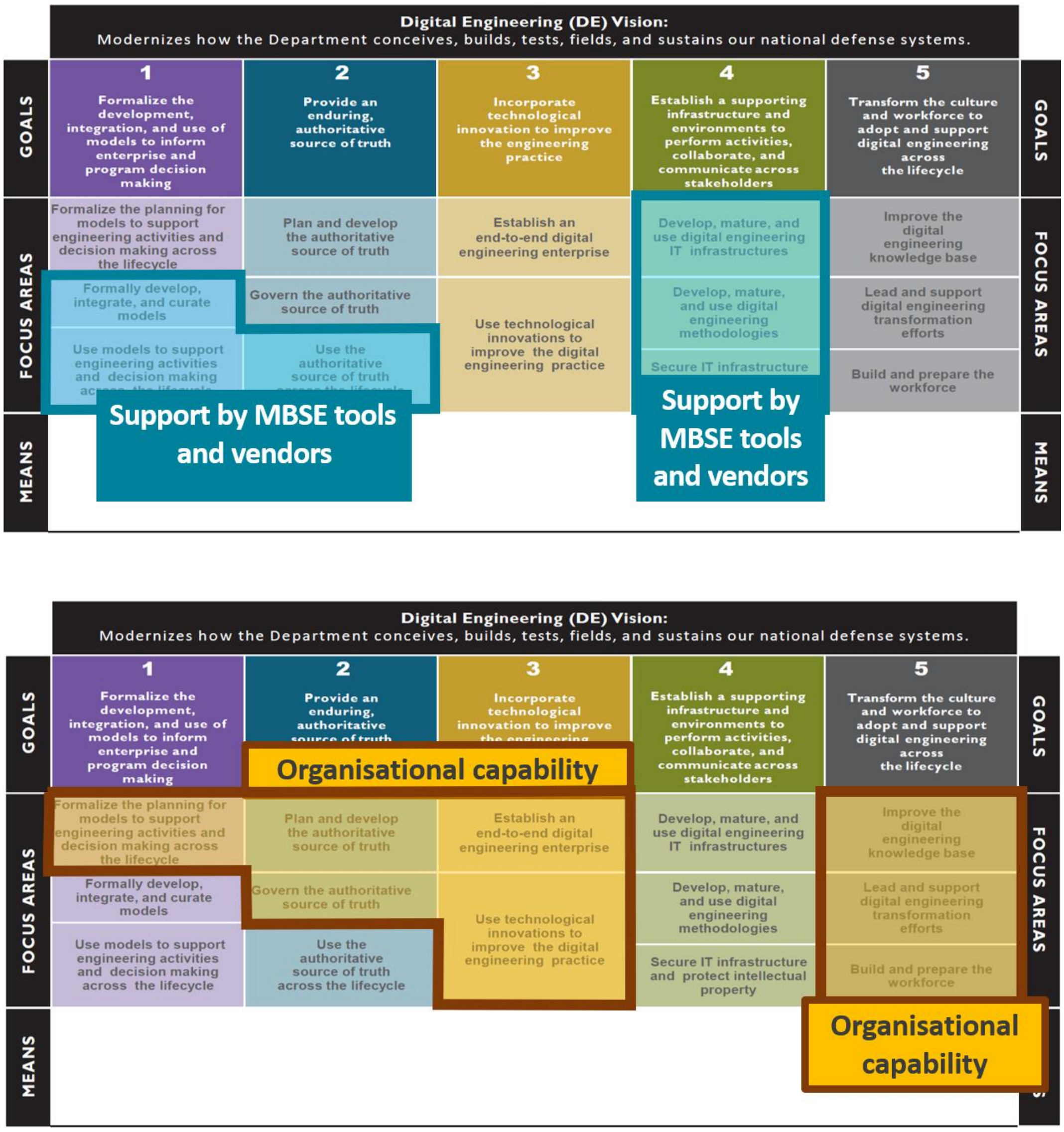

Figure 12 - Digital Engineering goals and support of MBSE tools/vendor (top) and the required organisational capabilities to be developed (bottom)

5.5 Leading MBSE-Methods/Tools

During the MBSE-study, a series of (virtual) meetings were organized with suppliers of MBSE methods and tools. These meetings covered a significant number of leading suppliers, yet by no means these are the only vendors. These meetings provided valuable insights. They were, however, too short to reach a full depth understanding of the available methods and tools. With several tools ESI and their partners have hands-on experience and therefore deeper insights in the capabilities of these tools. The overview given below is not to be taken as the "ultimate MBSE-tool" overview. It should not be read as a MBSE-tool selection guide.

Together with the industry partners involved, a set of suppliers has been selected, based on existing contacts and on interest in their tools. As the study progresses, the set of contacted MBSE-tool suppliers will be extended and insights into the capabilities and limitations of their methods and tools will be deepened.

The sections below give a high-level overview of our observations from meetings with MBSE-tool suppliers, tool demonstrations, experiences from ESI research projects and from pilots of the partners of ESI involved in the project.

In the study, we met with three companies that deliver a full-fledged model-based method and tool suite, including (i) core-MBSE modeling, (ii) simulation, (iii) 3D design and (iv) PLM and manufacturing oriented: Dassault Systèmes, PTC and Siemens. We will give a description of their methods and tools first. After this, we will give an overview of tools that have a smaller scope: Arcadia/Capella, Genesys, SystemComposer, ModelCenter, and Sparx Enterprise Architect.

Dassault Systèmes: Cameo Systems Modeler - CATIA

The Cameo Systems Modeler[16] is a systems modeling environment provided by Dassault Systèmes. It supports the MBSE process, using SysML or SysML-like modeling languages. The environment can be used by a single user or in a cloud solution, allowing multiple teams to cooperate, using the same models.

The environment has many open interfaces to industry standard third-party tool environments. Some of them are for integration with requirements management and traceability tools, as well as import, export and synchronization with Enterprise Architect, DOORS and Requisite Pro. Cameo provides support for traceability of requirements and gap analysis throughout the model. Parametric modeling is supported by simulation toolkits and a parametric plugin. Cameo offers a built-in math solver, but it can also interface with MATLAB, OpenModelica[17] or Mathematica[18]. State-machines can be simulated by a built-in simulation engine.

The tool and language can be adopted to the users specific needs. Cameo comes with a scripting engine which supports multiple scripting languages. Furthermore, a DSL engine allows for adaptation

16 https://www.3ds.com/products-services/catia/products/no-magic/cameo-systems-modeler/
17 https://www.openmodelica.org/
18 https://www.wolfram.com/mathematica/

to a specific modeling domain. To allow compatibility with other document-based workflows, export and publishing features are included in Cameo Systems Modeler.

PTC: Windchill Modeler

PTC[19] is a major supplier, active in providing solutions in the area of the Digital Transformation and a strong supporter of the Digital Thread way of working. One of their products is the Windchill Application Suite[20], a Product Lifecycle Management system, which includes the Windchill Modeler[21], which is a solution, intended to support MBSE[22].

Windchill Modeler has a strong emphasis on UML (Software), SysML (System) and OVL (Variability), but also supports BPMN and UAF (business and enterprise), as well as IE (data). The solutions supports built-in simulation as well as integration with external tools, e.g., Matlab/Simulink to allow co-simulation. Also, integration with tools from other vendors, e.g., DOORS for requirement management, is provided. PTC solutions support traceability and multi-project, multi-site teams working together.

Siemens: System Modeling Workbench

Siemens is one of the main suppliers of Product Life Cycle Management (PLM) systems. With TeamCenter[23], they provide a full-fledged PLM suite that is used by many leading industries. Siemens has integrated MBSE in TeamCenter: the System Modeling Workbench.[24] As the workbench is an extended and professionalized version of Arcadia/Capella, its characteristics are very similar to those of Arcadia/Capella as described below, therefore we have refrained from giving a detailed description of the workbench in this section.

In addition to the standard functionality of Capella, Siemens has created added-value by integrating MBSE with the rest of their TeamCenter functionality (PLM, 3D modelling, simulation, etc.) and by supplying Siemens-specific extensions to the standard functionality. By combining MBSE with their full PLM system, Siemens has created a fully integrated suite, similar to Dassault Systèmes and PTC.

Arcadia/Capella

Arcadia is a model-based system engineering method supported by Eclipse-based tool Capella[25]. It started as an initiative of Thales system engineers in the early 2000s, who at the time could not find a commercial tool that would fit the company's MBSE needs [30]. Nowadays, the core Capella tool is available as open source (as are a number of add-ons), with commercial support (including training, tool customization) provided by the company Obeo[26]. Siemens has integrated Arcadia/Capella as

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19 https://www.ptc.com/
20 https://www.ptc.com/en/products/windchill
21 https://www.ptc.com/en/products/windchill/modeler
22 https://www.ptc.com/en/technologies/plm/mbse
23 https://www.plm.automation.siemens.com/global/en/products/teamcenter/
24 https://www.plm.automation.siemens.com/global/en/products/collaboration/mbse-model-based-systems-engineering.html
https://www.plm.automation.siemens.com/global/en/our-story/newsroom/system-modeling-workbench-teamcenter/43935
25 https://www.eclipse.org/capella/
26 https://www.obeosoft.com/en/

"System Modeling Workbench" to its PLM Software (TeamCenter). Capella models, stored in the Siemens Teamcenter environment become artifacts that are part of PLM.

Arcadia is both a method and a domain specific language. The method structures system architecting steps and resulting diagrams into layers, similar to other architecting standards such as NATO Architecture Framework [31]. The basic usage of Arcadia is functional analysis and allocation of the functions to components. The language of Arcadia is *architecture* domain specific, inspired by UML/SysML, enriched with typical architecting concepts, such as functions, function ports and functional exchanges [30].

Arcadia/Capella models are descriptive: they capture functional and system decompositions, and operational use scenarios. Extensions to the core Capella tool then can connect these models to 3rd party analysis frameworks. Currently, a growing research and practice community is active under the umbrella of the Eclipse Foundation to create such extensions to simulation tools and concepts.

Vitech/Zuken[27]: Genesys

Genesys is a tool (created by Zuken-Vitech)[28] supporting the description of architectures and system designs, from the product ideation phase (requirements) to the validation and verification phase. One of the most prominent features of the tool is its focus on foundational SE concepts, including V&V (e.g., covering both V&V requirements and associated V&V test activities). These underlying concepts, their meaning and relations represent the mental model of the system engineer. They are captured in the underlying structure of the tool. This fosters alignment with the way-of-working and thinking of system architects and engineers. These semantics are enforced throughout the development of the models, assuring consistency and design integrity of the system and its properties.

Genesys provides infrastructure for connecting to other tools, such as Excel, MATLAB, Phoenix Model Center (see the description of this tool on page 29), etc. The tool also provides support for choosing a preferred design methodology and for a variety of representations fitting to the engineering roles. The collaboration aspect is covered by a live connection model, role-/based access permissions, and a lightweight versioning system.

MathWorks: SystemComposer

SystemComposer[29] is a MathWorks MBSE tool. Using a SysML'ish language, it allows systems engineers to create models of their systems like other MBSE-tools. A specific characteristic of SystemComposer is its integration with other tools of MathWorks, such as MatLab and Simulink. SystemComposer offers a modelling framework to create systems models that integrate simulation and analysis models created with these tools into system-level simulation and analysis models. System Composer adds capabilities for modeling integration between systems, filtering large models into manageable views, capturing important system and component properties, allocating between different descriptive architecture models, directly connecting system architecture models to software functional models, and flowing data down into specialized design tools [32].

27 Vitech has recently become *a Zuken company*
28 https://www.vitechcorp.com/genesys_software/
29 https://www.mathworks.com/products/system-composer.html

System Composer and Simulink are part of the same development environment and are tightly coupled, so it is easy to create, access, and run Simulink models within System Composer, by embedding those Simulink models within the components of the architecture model. The dataflows into or out of the component in the System Composer architecture model are immediately synced with the inputs or outputs required to run the Simulink simulation model and vice-versa. With System Composer, models can begin as an early way to capture concepts and mature into systems integration models that describe the integration between subsystem models [32].

Phoenix Integration/Ansys[30]: ModelCenter Integrate

ModelCenter Integrate[31] is a non-typical MBSE tool, as it is addressing the missing part 'in the middle'. It is a generic integration framework to connect typically physics simulation models to standard MBSE tooling. In doing so, it helps to connect diverse groups in product development, notably the system engineers and system architects to the hardcore analysis specialists in various disciplines (e.g., mechanical, electrical, cost, manufacturing).

The tool bridges the gap between systems engineering models and specialist domain engineering models. It allows to convey analysis requests for given system requirements and specifications for simulation and calculation, while the analysis results such as performance estimates, parameter sensitivity studies, and conformance assessments can be fed back into the MBSE environment. Phoenix Integration stated that the tool does not target dynamic simulation (e.g. *model-in-the-loop*); rather it targets (multi-disciplinary) performance and trade space analysis.

ModelCenter is a generic platform - it can connect to the tools Capella, Enterprise Architect, PTC, and Dassault's Cameo System Modeler, Excel, and even Fortran code (there seems to be no limit). ModelCenter can use SysML-based parametric diagrams that are defined in, e.g., Rhapsody, MagicDraw, WindChill Modeler, or Genesys. The tool can be used to analyze the dependencies between the parameters and data.

Sparx Systems: Enterprise Architect

Enterprise Architect (EA)[32] is a modeling environment supplied by Sparx Systems. It is a generic integrated modeling platform, capable of supporting multiple domains, e.g., business and IT, software, systems engineering, real-time and embedded development. Some of the supported languages are UML, SysML, BPMN, and architecture frameworks like TOGAF and UPDM, using plug-in extensions. Also import and export capabilities of information, using the NIEM (National Information Exchange Model) are supported. To be compatible with a documentation way of working, documents can be generated from the models.

The environment can be used by a single user as well as by multiple teams in a collaborative mode. The latter can be supported by the cloud-based solutions. Sparx Systems indicates that the environment is intended for large teams and that it is capable to handle large models with short

30 Recently, Phoenix Integration has become *an Ansys company*
31 https://www.phoenix-int.com/product/modelcenter-integrate/
32 https://sparxsystems.com/
https://sparxsystems.com/products/ea/index.html

response times. Version control is also supported. Furthermore, it offers traceability of features from requirements to analysis and design.

Summary of Observations

Historically, MBSE has been associated with the SysML language and SysML models only (Capella and SystemComposer being exceptions, having their own modelling languages). Most MBSE tools, however, have internalised various additional functionality, or added links to other modelling tools. MBSE tools such as, e.g., Windchill (PTC) and Genesys (Vitech/Zuken) have integrated Ansys ModelCenter to support quantitative modelling; Cameo System Modeler (Dassault Systèmes) is part of a large Dassault 3DEXPERIENCE tool suite with CAD modelling and manufacturing tool support; Teamcenter (Siemens) combines Capella with extensive PLM support.

MBSE tools and methods require a steep learning curve and large upfront investment (due to the nature of the language, SysML is harder to learn for engineers lacking a strong software background). Beyond learning the tools, a further and more daunting challenge reported is how to make the methods and tools effective in an organization. Vendors sometimes maintain relations with consultants to support this process. Also, staff needs to be trained or acquired; methods may need tailoring to fit the organization’s way-of-working, or the way-of-working needs to be adapted to make the methods and tools effective. Since MBSE tools are often used to connect models from different disciplines, organizations need to align across their departments and disciplines to reap benefit. Finally, some information ‘transformations’ (e.g., model to document) may be needed to achieve buy-in from (non-technical) stakeholders.

A further point of note is that tool vendors started to develop the MBSE tools from different origins. Dassault came from the CAD modeling origin, whereas Mathworks’ SystemComposer came from a simulation origin. This heritage is reflected in the capabilities of the tool and the ‘center of gravity’ of their MBSE capabilities. Hence, fit of the tool with the organization could vary depending on the type of system, and the type of development complexity being faced.

6 Industry Pilots

6.1 MBSE for Configure-to-Order at Vanderlande

Vanderlande[33] develops and delivers logistical solutions to their customers in a range of application domains (passenger and baggage handling at airports, warehousing and parcel distribution). Since their customers typically have their own, optimized logistical processes, and since these solutions must be positioned in the physical environments of their customers, the solutions delivered by Vanderlande are typically customer specific. Delivering customized solutions that are optimized to meet customer requirements and preferences is one of the key values of Vanderlande.

Vanderlande is in the process of changing the way they service the market by introducing a configure-to-order approach, based on a platform-approach and MBSE. They want to be able to create most of their customer-specific solutions by combining pre-developed (tested and internally released) platform modules.

A key challenge of their approach is: "how to assure that the solutions offered to our [Vanderlande's] customers remain compliant to the platform *and* to the customer requirements" [24, p. 8]. The underlying complexity challenges they have identified are:

- many combinations can be made when configuring a customer solution based on a platform;
- customers tend to have very detailed and specific requirements;
- platform development and customer solution delivery are progressing over time [and need to stay connected] .

Vanderlande has chosen to use MBSE to address these challenges (see Figure 13 from [24, p. 11]):

- sales will use a [model-based] sales configurator connected to platform models;
- changes to platform and customer solutions will be observable in models[34];
- deliverables will be automatically created from platform and solution models;
- a taxonomy of the *one language*[35] and design principles will be in the models.

In the MBSE-study, Vanderlande shared with us their approach to create meta-models establishing this taxonomy (the *one language*). The taxonomy defines a meta model for the platform; it defines a common domain language, and it defines the models and their relations. Using the taxonomy, platform modules and customer solutions can be described. In a joint ESI-Vanderlande project (RunBase), we developed meta-models to describe variation points of the platform components and mechanisms to configure platform components in the design of customer solutions. All meta-models have been described with SysML using Enterprise Architect [5].

33 https://www.vanderlande.com/

34 Vanderlande has observed that the "absence of a clear change propagation visibility reduces reliability and increases vulnerability to mistakes". Using models as the authoritative source of truth, changes to products and solutions will be consolidated by changing the corresponding models. Due to the connected nature of MBSE models, such changes will ripple through the model and changes and their impact will be observable in models.

35 Vanderlande aims to develop a common language by introducing models and meta-models]

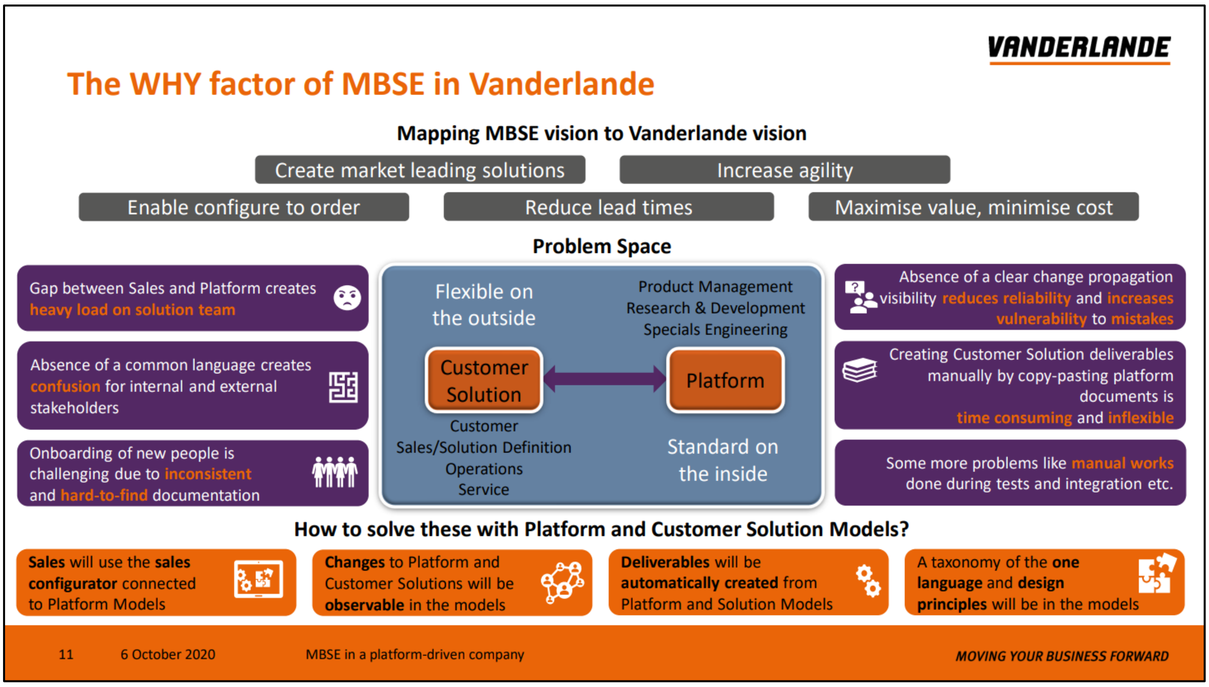

Figure 13 - The motivation and ambition for MBSE of Vanderlande (from [24])

A specific observation is that MBSE does not provide specific methods and tools to support the platform-based approach and configure-to-order approach chosen by Vanderlande. They see (as in Figure 14 from [24, p. 14]), two levels of MBSE:

- MBSE for creating customer solutions, where the solution models are typically created by customer and sales-oriented teams.
- MBSE for creating the platform, where the models of the platform and of platform component are created by R&D and technology-oriented teams.

In platform-oriented solution-design processes, the designs are created by combining existing platform components, rather than by using the decomposition processes that are typically found in MBSE-methodologies. What is important in these processes is to hide complexity of the platform and its components as much as possible. Model-based techniques are needed to (quantitatively) determine the qualities of composed solutions without exposing the platform's complexity: sales teams need tools to validate that the qualities of the designed solution meet the customer requirements. Furthermore, methods and tools are needed to validate that the solution complies to the capabilities and constraints of the platform.

In the platform-oriented processes, the platform components are not designed for a specific customer, with specific customer requirements. Instead, the platform and its components are designed to provide building blocks that can be used to create a range of customer specific solutions. Configurability, diversity and variation points are key elements in these platform-oriented processes. So far, no MBSE-methodologies have been identified that address the specific challenges involved.

Finally, Vanderlande needs to bring these two worlds together: models that contain the complexity and details needed for R&D, while hiding complexity from the solution designers.

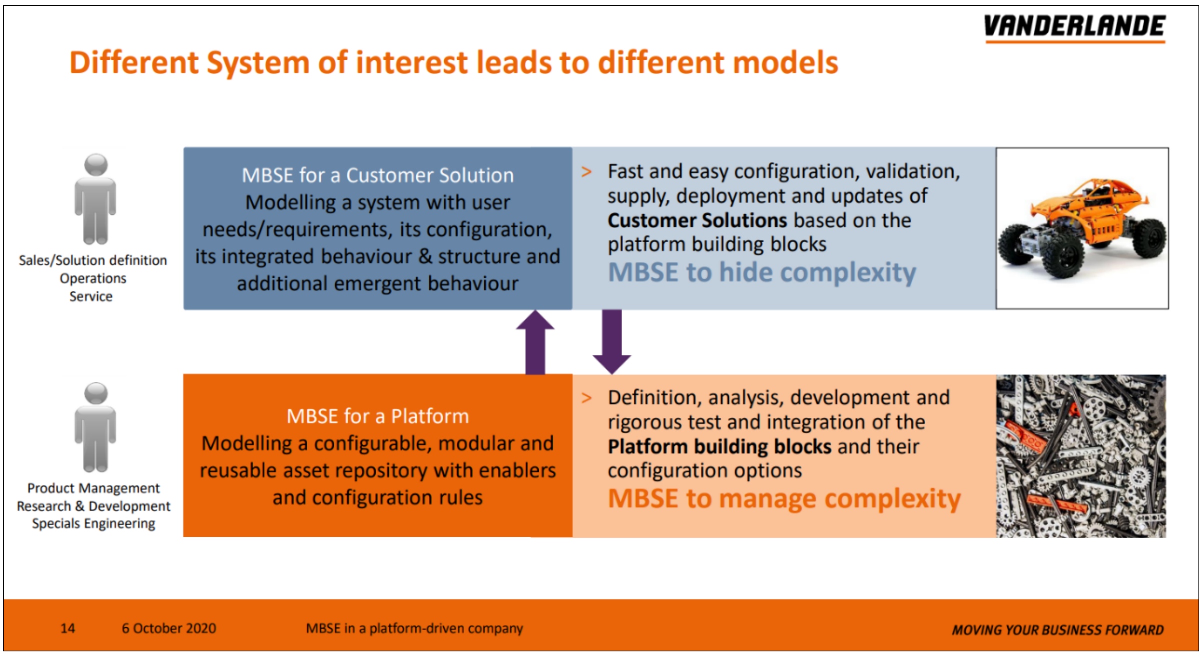

Figure 14 - Two-levels of MBSE application: solution development and platform development (from [24])

6.2 New product development at Philips

Philips[36] is a global company with focus on healthcare and personal health solutions. The presented pilot was provided by the Systems Engineering Center of Excellence (SE-CoE) and demonstrated a modelling example of a patient monitoring system.

The SE-CoE is a corporate group, one of their objectives is to introduce and support MBSE in the organization. They co-develop with the business R&D teams the methodology and processes as well as select and introduce tools and infrastructure as part of the systems engineering transition program of Philips. The primary objective is to increase the productivity of the Philips R&D centers and the quality of the output. Their approach is to actively support teams by multi-day training programs and to support teams at the work floor during the introduction phase. The organization has a strong corporate support and reports to the head of Product

The current focus is on covering the top of the V model through modeling techniques for capturing requirements and needs, architectural design, and testing and verification, including the relationships between them. The longer-term roadmap also addresses simulation at various levels of detail, connected to the overall model.

At this moment, pilots are running at selected groups in the organization. A challenge in the domain of medical equipment is that such equipment needs certification. At this moment national authorities, such as the FDA, require documents and do not accept models. Consequently, when MBSE is used and models are the authoritative source of information, documents must be generated from these models for the required regulatory submissions.

The pilot presented was about the Patient Monitoring Systems of Philips Böblingen (Germany). The selected MBSE tool to run this pilot is the Cameo Systems Modeler, provided by Dassault Systèmes.

[36] www.philips.com

For the detailed design many modeling and simulation tools are already in use. The pilot fills the gap towards system level, using SysML for a structural breakdown. Currently, there is no hard connection with these detailed designs. By transferring this system level from a document based towards model-based way of working, there is more focus on the real contents, completeness of information and identification of risks. A document generation step is still required, however, because of demands by regulatory authorities. An additional issue is that they only accept textual information, the SysML diagrams, such as, activity diagrams are not enough on their own. Paper documents have to be physically or electronically signed off. The methodology followed is based on the ideas of Tim Weilkiens and the SPES methodology, but more detailed. A Philips proprietary SysML profile is used which also includes automated checkers. At this moment, a small number of people are using the method, but this group is expected to grow. A substantial effort has been made to introduce this approach in new teams. They receive an introduction by having a multi-day training. During the project, experts are embedded in the project to provide active support on the job. A full-scale example for a patient monitoring solution has been provided for training purposes

6.3 Configuration Management at ASML

ASML[37] develops and manufactures photolithography systems used in semiconductor industry for mass-production of microchips. ASML is the leading supplier of these machines on the global market. Among its customers are fabrication plants realizing the chip designs of other companies, companies selling their own designed chips, and companies making chips to integrate them into their products. In 2020, The Economist described ASML as “a low-key Dutch company [that] has cornered a critical link in the global electronics supply chain” [33].

The key motivation to start using MBSE in ASML is coming from the need to manage ever increasing complexity of ASML systems through the whole product lifecycle. The vision is to have a "digital thread" [34, 35] that relates system requirements to the real system through the system architecture models and more detailed design models (as shown in Figure 16).

ASML started with MBSE by taking a “narrow instead of shallow” approach, starting with the MBSE activity that brings the most value. Apart from using the models for analysis and understanding, they are also used to define product configurability. The models are used to express compatibilities and dependencies between system elements, serving as an invaluable source of configuration information and rules.

The reason to start with modelling system configurations is that ASML has a large install base, some machines are in the field for decades. A challenge for ASML is not only to build the right system, but also to maintain these systems in the field. Maintenance and upgrades of operational machines is important to both ASML and its customers. For these reasons, ASML has chosen to start with MBSE to streamline configuration management.

The knowledge required has large number of details, the engineers introducing new features must ensure backwards compatibility, so they also must understand older configurations. ASML has grown tremendously over the last decade and now has more than 30.000 employees. Therefore, another

[37] https://www.asml.com/

motivation to start using MBSE was to make the knowledge of the complex systems more integrated and accessible, instead of scattered across many documents and information systems.

The goal of these models is to relate system architecture diagrams and product architecture, as shown in Figure 15. Architectural models are created in Capella (System Modeling Workbench) and stored in TeamCenter. These models contain all available system elements and the allowed (or valid) combinations of system elements. The ability to store the models in Teamcenter, the primary product data management tool used in ASML, is critically important. This will allow ASML to create links between the bill-of-material items and the system model objects, finally connecting the actual configurations with the defined configurations.

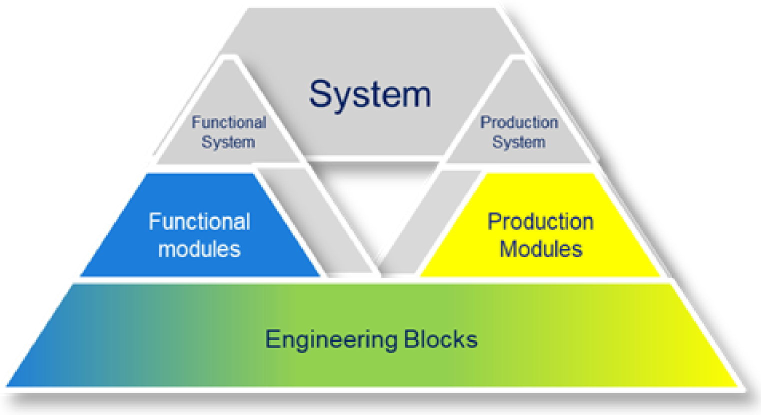

Figure 15 - On the left side, system architecture models are created. They contain all possible variants of components and functions. On the right side, the bill-of-material model describes what ends in a particular product. (from [34, 35])

ASML has a plan to introduce MBSE step-by-step. At this moment, relations with requirements documents are established with the first Capella system models. ASML's next challenge is to establish and maintain alignment between the system model and the various detailed design models created by the mechanical, electronic and software engineers. This alignment is crucial to for the realization of the digital thread, to give ASML more confidence that its products perform according to customer expectations.

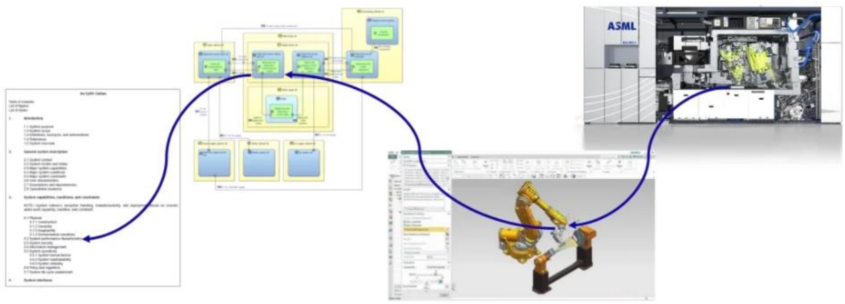

Figure 16 - The digital thread view (screenshot from [34, 35]) The architectural model is part of the digital thread, and connects requirements with more detailed design that leads to the actual product

6.4 Reference Architecting at Thermo Fisher Scientific

Thermo Fisher Scientific [38] has a long history of creating state-of-the-art transmission electron microscopes (TEM). Their leading position in various markets is based on the extremely high performance and quality of their TEM products and their dedication to customer demands. The challenges associated with this are the development effort of essentially customer-specific products (non-standard requests) and subsequently managing the large diversity of products in the field. The very high system complexity combined with the very long lifetime of TEMs is causing additional challenges. The solution directions are expected to be found in model-based systems engineering, and developing a reference architecture, to enable the management of modules and system configurations across the platform.

This requires a significant change in the way of working including a transition towards systems thinking for the entire organization. As a first step, a reference architecture has been developed (together with ESI [6, 8, 36]), describing the fundamentals of the TEM product portfolio (e.g., functional decomposition, system decomposition, variability in realizations). This basic description is currently extended in various ways (business driver analysis, CTQ flow down analyses, taxonomy development, diagnostics analyses, platform development, etc.). Thermo Fisher Scientific is in the process of embedding all of this into the daily way of working (including the development of guidelines for many engineering activities).

Initially, the approach focussed on capturing systems knowledge in models and on the initial ideas of how to use the reference architecture. In this phase, tool selection was not the primary concern. As time progressed, and the application of the methods scaled up, mature and easy to use support methods and tools were required. Thermo Fisher Scientific has decided to use MBSE-methods and tools for modelling the TEM Reference Architecture (in particular Arcadia/Capella).

This tool, possibly equipped with several plug-ins, promises to tackle the variability and configuration challenges. The current work is focussing on how to express the reference architecture, the many TEM configurations, and the non-functional system models in the Capella tool using the Arcadia method.

Further research is on linking the architecture models to simulation models, as mentioned by Thermo Fisher Scientific in [37]. The goal of bringing together workflows, functional decomposition, configurations, and simulations, will enable the prediction of performance of alternative system configurations. This requires that simulation models be composable in a way that enables exploring alternatives in a desired design space, e.g., to parallelize or pipeline specific sub-tasks. This particular research activity is part of the MBSE work on identifying the right connections between systems' building blocks, their properties, the functions they perform, and composable simulation workflows.

6.5 Systems Engineering at Thales

Thales, as an aerospace and defense organization, provides highly complex "engineer-to-order" systems to its professional/defense customers. Examples of such systems are combat management systems onboard of navy vessels, satellites, but also railway systems, trains, and in-flight entertainment systems onboard of commercial aircraft. Managing the increasing complexity for the

[38] https://www.thermofisher.com/nl/en/home.html

development of such highly advanced "engineer-to-order" systems is a natural fit for Model-Based Systems Engineering. In fact, Thales developed in-house the Arcadia/Capella method and tool (see section 5.5) which was later open-sourced.

Thales was one of the first to embark on the transformation from "traditional" SE to Model-Based SE, partly due to defense customers requesting MBSE to be applied in their projects. In Thales Hengelo[39], the main focus areas of the MBSE transformation are the System Architectural Design, the decomposition in SW/HW/FM Architectural design, and the management of the relations with enterprise architecting, various other engineering disciplines, and V&V effort [38].

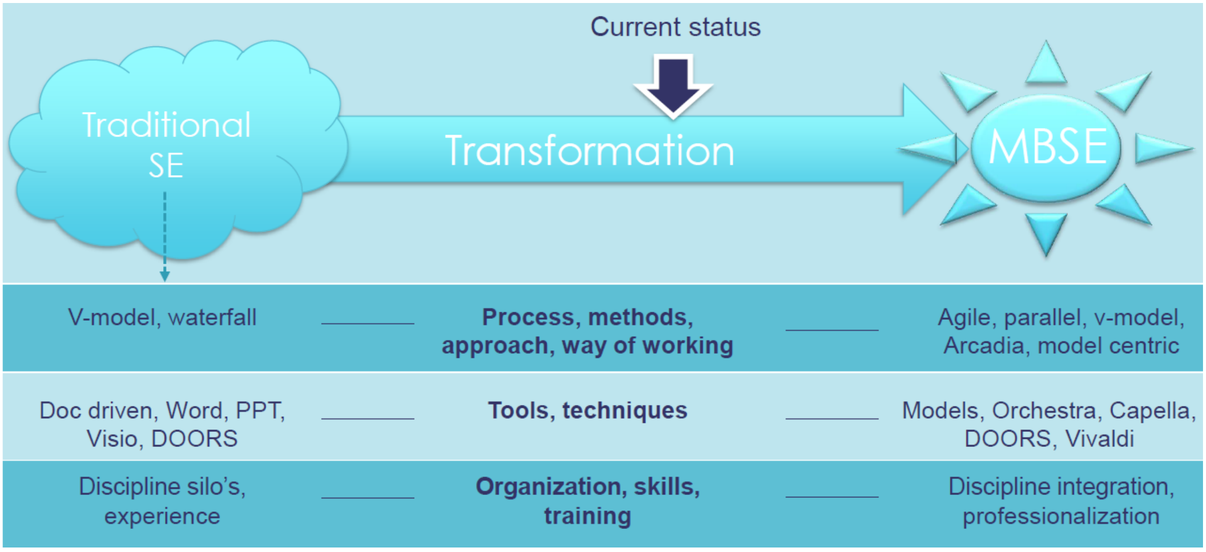

Figure 17 - MBSE Transformation process at Thales Hengelo (source [38])

The three pillars in the transformation are the following (see Figure 17):

- processes, methods, approach, way of working;
- tools and techniques;
- organization, skills, and training.

The waterfall way-of-working is in transition to an agile, parallel, model-centric way-of-working, still around the V-model and a strong process including V&V to assure systems meeting customer demands.

With respect to the tools and techniques, the Capella tool supports the Arcadia method, and further tools are integrated into a tool suite for managing requirement, configurations and variants, support document generation, and also help integration, verification and validation.

With respect to the organization and skills, much emphasis is put on discipline integration, and professionalization. Objective is to avoid silos. Training is needed to spread experiences into the organization, and to improve collaboration and co-engineering with partners and suppliers through (model-centric) system to sub-system partitioning and transition management with federated models.

[39] https://www.thalesgroup.com/en/countries/europe/netherlands

This transition is still ongoing. Thales' strategy is to roll-out a "tooled-up process" to support this transition with also practical guidelines. Firstly, the transition focused at Systems Engineering only, but now is widening towards including or connecting to specialized disciplines (such as HW, SW, safety, security engineering and Integration, V&V). Key Thales learnings are to set clear modelling objectives, share the models with ALL stakeholders to make them THE reference, and institute regular model-reviews.

6.6 Factors influencing MBSE introduction and added value

Summarizing the pilots and interactions with MBSE tool vendors, a number of factors have been identified that influence the applicability and added value of MBSE for an organization, based on today's MBSE methods and tools. MBSE has been first applied in Aerospace and Defense. Both these domains are characterized by large-scale "Engineer-to-order" projects for systems with high complexity in multi-disciplinary physics and mechatronics. From then on other domains have adopted or experimented with MBSE. Based on the success reports of application of MBSE in various domains and insight in the nature and strengths of MBSE methods and tools, here a summary of inferred influencing factors is given. These factors indicate the likelihood of added value for MBSE for an organization over "just" doing Systems Engineering with (disconnected) models.

Figure 18 presents an overview of these factors which have been categorized along five major aspects:

- the type and nature of the systems developed;
- the nature of stakeholders and stakeholder interaction;
- the context and environment in which the system operates;
- The nature of the R&D process;
- the nature of the system's production and lifecycle.

Unsurprisingly, these influence factors are generic and simplifications of any specific situation. They are offered as "thought-starters": interpretation and assessment in the context of a specific organization and product (line) remains required.

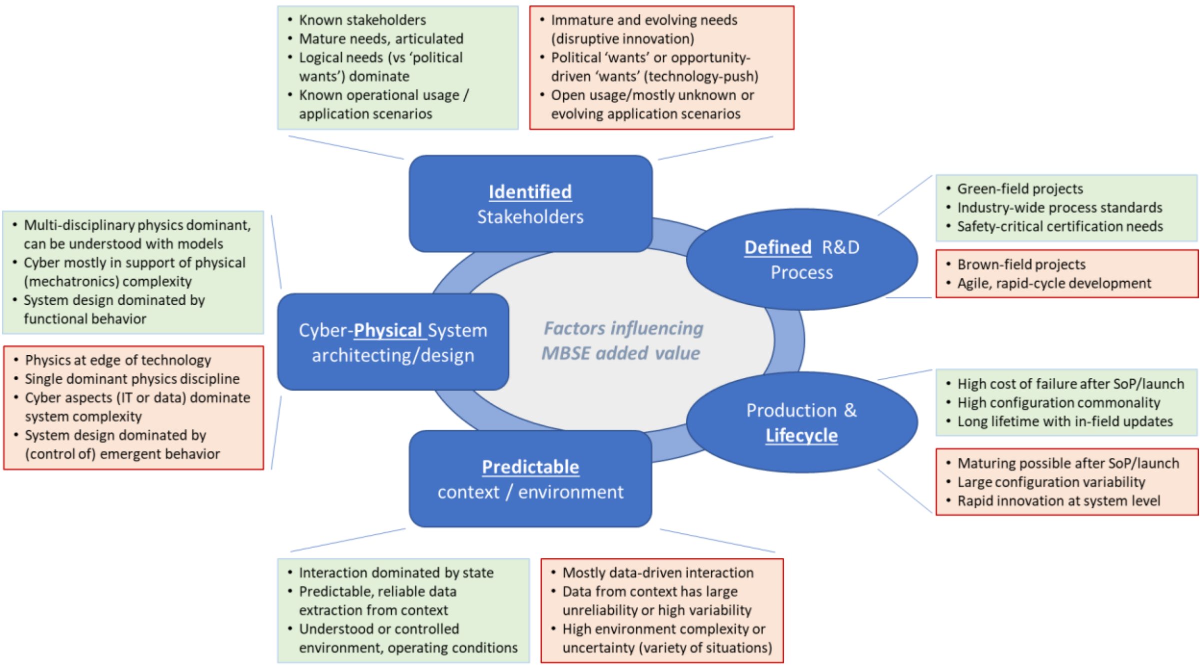

Figure 18 - Factors influencing the added value of MBSE (positive factors in green, negative factors in red)

As shown in Figure 18 on the left, with respect to the nature of the system, MBSE can add significant value when the system to be developed contains a large design challenge of balancing multi-disciplinary physics, as in aircraft or spacecraft design (hence the underlined Physical to emphasize that modelling of (multi-disciplinary) physics is a key driver for MBSE). However, when cyber aspects, or management of emergent behaviour dominates complexity, then MBSE is less applicable as these aspects are less well captured in the MBSE-type of models.

With respect to stakeholders (Figure 18, top), these should be known and able to articulate their needs well (hence the underlined Identified). A successful MBSE application requires well-articulated system requirements, which for the basis of traceability into the design and verification of its decomposition and properties. Stakeholders should be versed in expressing their needs in a form suitable for MBSE.

With respect to a system's context (Figure 18 bottom), this context should be understood, such that it can be captured in models to perform system-in-context analysis (hence the underlined Predictable). When this context sees large uncertainty or sees mostly data-driven interaction with large uncertainty, then this is difficult to take onboard in MBSE approaches as these are typically function-oriented or require very specialised approaches. In automated driving developments, e.g., large and detailed environment models are needed to drive system developments in order to handle the wide variety of roads, road users, and road infrastructure across the world and the impact of this on the system.

With respect to the R&D process (Figure 18, right and top), green-field projects starting from scratch benefit most from MBSE as this allow complete use of MBSE over the full design scope (indicated by the underlined Defined). Incremental design upgrades of older systems with a large legacy present complications in that many of the (existing) system components do not have models nor necessarily are completely documented. Often know-how is lost to the organisation as the original designers of such components may have left the organisation. Recreating such know-how and infusing this in MBSE context, would place a high overhead and time-to-value on application of MBSE. In such situations, an R&D project for an incremental change cannot be expected to bear the cost, effort and time overhead of MBSE introduction.

Finally, with respect to Production and Lifecycle (Figure 18, right and bottom), MBSE usage is particularly suited to minimise unacceptable risks when a high cost of failure could occur after launch or Start-of-Production (SoP) (indicated by the underlined Lifecycle). This is typically the case with mass-produced systems, e.g., road vehicles or, medium-size product series of large value systems, such are commercial aircraft. Also, MBSE can ease design and qualification of upgrades during the operational lifetime of the product. However, for products that can be launched quickly as a minimally viable product and then quickly matured based on field feedback (e.g., using an Agile/DevOps type of approach with incremental updates in an SW intensive systems) then MBSE overhead may be too much. The same holds for systems where rapid innovation at system level or system level concepts still occur. Then investment in models of quickly obsolete parts or system concepts may not outweigh the effort.

Most MBSE methods and tools implement a variant of the Requirements, Functional Architecture, Logical Architecture, Physical Architecture (RFLP) approach. This approach has been particularly well suited for certain domains and organisations. This section and Figure 18 have provided a set of factors to rationalise why MBSE has been successful, and what underlies the added value in those domains. This section also provided contrasting factors for when MBSE added value could be less or not significant over just doing Systems Engineering with (disconnected) models.

As many systems today are complex and may consist of heterogenous subsystems, these factors could also be helpful to determine in which of the subsystems MBSE could be introduced first. Furthermore, some of the factors hindering MBSE methods and tools in achieving added value can be topics for further research (see also the next steps described in section 7).

7 Observations, Recommendations and Next steps

As described in the sections before, ESI (TNO) and their industrial and academic partners explored the ambitions, opportunities and challenges of introducing Model-Based Systems Engineering in the high-tech equipment industry:

- workshops with ESI's industry partners to explore their MBSE-ambitions;
- workshops with ESI's academic partners to identify MBSE-focusing academic research programs;
- workshops and interviews with vendors of leading MBSE solutions;
- visits to the industrial partners of ESI for presentations and demonstrations of their MBSE pilot projects.

In the previous sections, an overview has been given of the results of these activities and of several observations and our conclusions. In this section, an overview will be given of the main observations and conclusions and of the next steps.

7.1 Observations and Recommendations

The following have been our main observations during the project:

- the high-tech equipment industry needs MBSE to be introduced in a brownfield;
- Model-Based Systems Engineering can easily be limited to the creation of SysML'ish diagrams for the systems engineers without connections to other engineering disciplines and thereby have limited impact;
- the industry needs MBSE for platform-based R&D (compositional approaches);
- the industry needs solutions to deal with large system diversity;
- the industry needs solutions for modelling system qualities with quantitative models;
- the industry needs solutions to combine MBSE with agile R&D approaches;
- the industry needs guidance/transition paths to unlock significant value through appropriate introduction/embedding of MBSE into the organisation (including developing the systems engineering competencies that are needed as a prerequisite for successful MBSE).

In our IDEW'21 presentation [3], we summarized the main observations about the industrial needs as in Figure 19:

> The industry needs the consistency, completeness promised by MBSE ("authoritative source of truth"), and they need the cooperation/collaboration platforms that most MBSE-tools offer. In addition, they need ways to leverage the value of MBSE in their business environment, dealing with the brownfield, dealing with evolutionary delivery requiring knowledge about past system generations, and leveraging their investments in platforms.

Without going into more details, each of these will be briefly elaborated below.

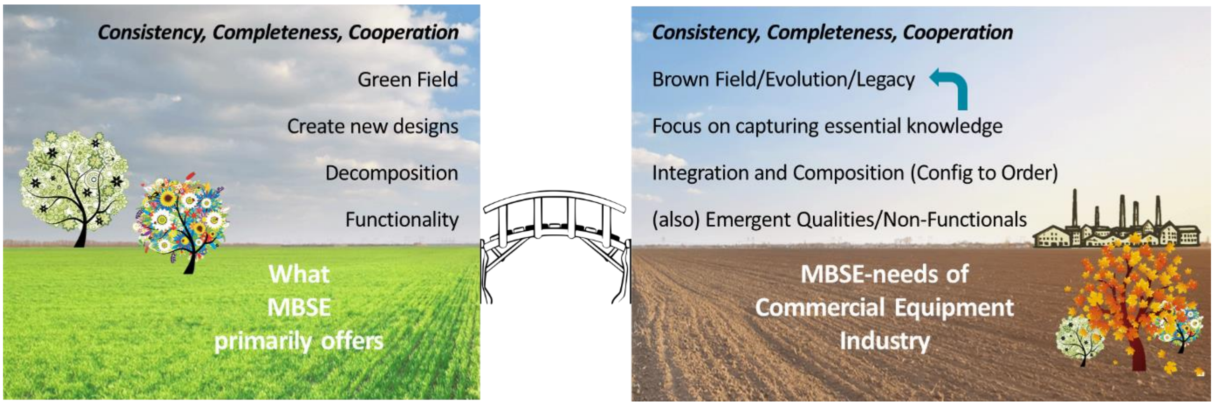

Figure 19 - The Gap between MBSE and The Industrial Need [3]

MBSE needs to be introduced in a brownfield industry

As discussed in *Greenfield versus Brownfield* on page 16, the high-tech equipment industry hardly ever has the pleasure of starting system development in a greenfield situation; for all our partners, the development of a new system starts from the design of the previous generation of systems.

Furthermore, the industry supports an installed base with systems that can be up to 15-30 years old. At the one hand, the installed base is a key business value; it gives them the opportunity to show their leading position in the market and it provides opportunities for upgrade and replacement sales and for their service businesses. At the other hand, supporting an aging installed base is costly and requires their teams to have knowledge of past system generations.

In this context, the following observations about MBSE are relevant:

- Fully switching to Model-Based SE will be a slow process, as converting the design documentation of previous generations of systems will be cumbersome and costly.
- As new system generations, are based on the designs of the previous generation, capturing the design of previous system generations in models is inevitable as solid starting point for using MBSE for future system generations.
- Key architecture and design knowledge is implicit and “in people’s heads”. To make models the authoritative source of truth, this knowledge about design rationale and design intent needs to be captured and to be made accessible. The introduction of MBSE can help, as models could serve as tool to capture this knowledge. It is not clear how current MBSE approaches can be used for this, however.

MBSE can easily be limited in scope and impact

As sketched in Figure 10 on page 23, MBSE typically starts in a confined domain: systems engineers creating system-level models to structure requirements and to allocate high-level requirements to system building blocks. To fulfil the ambition and promise of MBSE to make models the authoritative source of systems engineering information for all stakeholders across the full system life cycle, the following aspects are crucial for its application in the high-tech equipment industry:

- There is a need to bridge the gaps between the systems engineering discipline to the other engineering disciplines. The connection should be bi-directional: (i) systems engineering information should flow into the other disciplines and (ii) information from the other disciplines should flow back to the systems engineering domain to assure consistency.
- The industry typically develops systems in large, multi-disciplinary teams. To make the models the authoritative source of information, all relevant aspects need to be covered in models. Therefore, MBSE solutions must support multi-disciplinary models. This goes beyond functional RFLP-approach in contemporary MBSE methods and tools.
- If the models are the authoritative source of systems engineering information for all stakeholders, the information needs to be understandable by all stakeholders; the models describe the truth and are part of systems engineering communication. Techniques are needed to support communication with a wide range of stakeholders having different business and technical backgrounds.
- Most companies innovate by leveraging the added value of partners in their networks (supply chain partners, innovation partners, service partners, etc.). Therefore, there is a need for methods and tools to use models as the authoritative source of systems engineering information across organisational boundaries, in eco-systems and supply chains. As parties are typically involved in multiple networks, they likely must face models from multiple MBSE-methods and tools. Solutions are needed to deal with this diversity and to establish model-based cooperation among partners using different MBSE-methods and tools.
  Specific aspects in such multi-party value chains are: (i) models typically include company confidential information, mechanisms are needed to provide information at a need-to-know basis; (ii) partners in such value chains will extend models with their, more detailed, information for which round-trip modelling is needed to assure that information can flow through the models both ways.

MBSE is needed for platform-based R&D

The industrial partners of ESI all use product line engineering and platform-based approaches: building systems and solutions from a set of reusable building blocks. In this approach, system synthesis is a key element to be supported by MBSE:

- There is a need for methodologies and supporting tools to create models of platforms and platform components (a configure-to-order alike approach). In addition to the internal description of the platform components, models are needed describing their *external qualities* for a system/solution designed to select and combine platform components for integration into products and solutions.
- There is a need for methodologies and tools that allow selecting the optimal platform components and to configure them optimally to meet customer needs. For this, tools are needed to derive qualities of the system using models and transfer functions (calculating system qualities using models, starting from qualities of the selected components, their configuration and the composition of the full solution).
- To facilitate composing systems and solutions from platform components, there is a need for model-based methods and formalisms to describe multi-disciplinary (software, electrical, thermal, mechanical, EMC, etc.) interfaces (and interface standards) of components. The

interfaces should be described to assure that components complying to an interface specification can be used to connect with components that support the interface.

Solutions are needed to deal with large system diversity

As all industrial partners involved in the project deliver more and more customer-specific configurations, MBSE methods should deliver optimal support to deal with the resulting diversity. This aspect is often combined with the platform-based business and R&D models discussed above:

- There is a need for MBSE methods and tools that give full support for modelling and managing system diversity and configuration management. This includes formalisms that enable modelling of variation points.
- Methods, tools and formalisms are needed to cover the required system diversity without exploding the models in terms of size and complexity.
- Methods are needed to allow reasoning about individual system configurations as well as about the full product family.
- As incompatibilities of system components can result in unneeded diversity (system variants that do not exist to meet a customer-specific need, but only due to technical incompatibilities), model-based methods, tools and formalisms are needed to describe and control interface standards for system components (see also the related need above in the discussion about platform-based business and R&D approaches).

Solutions are needed for modelling system qualities (quantitatively)

In addition to creating innovative functionality, the industry needs to deliver this functionality with those properties that make their products fit-for-purpose. When companies have a configure-to-order approach, this becomes even more prominent: can they use models to determine the qualities of proposed a system configuration? Can they use models to find a system configuration that optimally (in terms of cost and value) provides the qualities needed by a customer? In previous research, ESI and Thermo Fisher Scientific defined value-driven architecting approach using models and concluded that:

- The RFLP-focus that is typical for MBSE-methods needs to be broadened to support quantitative modelling for system qualities and emergent properties. Simulation tools integrated into MBSE tools, such as ModelCenter, provide capabilities for analysing system qualities. Next steps are needed to develop methods for this and for embedding and validating these in systems engineering practice.
- In order to cover the full system life cycle, the RFLP-focus also needs to be broadened to support specific stakeholder views that are of a non-functional nature such as system manufacturing, transport, installation, service and maintenance, etc.

Solutions are needed to combine MBSE with agile R&D approaches

In the workshops with the industrial partners of ESI the classical waterfall approach has been under debate. Most companies adopt agile, CI/CD-based approaches and concurrent engineering approaches; initially for their software development and more and more also for their system development. Although creating an authoritative source of systems engineering information can contribute to streamlining such ways of working, there is also the fear that MBSE will reduce the overall agility. Therefore, the following need was expressed:

- There is a need for methods, processes and tools to combine MBSE with agile and concurrent R&D practices (all the way up to system-level).

Academic Research Programs on MBSE

During the project we discussed academic programs on MBSE with participating the academic partners. The outcome from that discussion was that: (i) there are several programs on systems engineering, but (ii) for the academic partners involved in the study, no programs specifically focussing on MBSE could be identified. In international research, programs are running (e.g., [39, 40]) and we are aware of additional (MB)SE programs at Dutch universities.

In next steps, ESI will extend the search for academic research and training programs on MBSE with a wider focus, including the academic partners of ESI not participating in the study, other faculties at the universities participating in the study, and the international partner network of ESI.[40]

7.2 Next Steps

After closing the MBSE-study at the end of 2021, several joint research projects have been started by ESI and its partners. In these projects, several of the aspects discussed above will be studied:

• Papillon 2022	Thermo Fisher Scientific	Methodologies for quantitative modelling of system qualities for a product family with many system variants/configurations (based on a Reference Architecture, using MBSE)
• ModelBase(d)	Vanderlande	Methodologies for embedding MBSE in an R&D organization in ways that create value for the business (mitigating related business risks). Using MBSE to describe a product platform and to compose customer specific solutions from these platform components.
• Canvas 2022	Canon Production Printing	Methodologies to develop reference architectures for platform-based product lines. Embedding of the approach as part of a company-wide strategy to make the transition to MBSE and platforms.
• iModular	Philips Healthcare (MRI)	Methodologies for models to describe multi-disciplinary interfaces of the building blocks identified in the platform architecture of a product line with product variants and customer-specific configurations.

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- ArchViews 2022 | Thales | Methodologies to connect (Model-Based) Systems Engineering to Software Engineering. How to cover non-functional aspects (Performance).

In addition, project proposals are being prepared to address topics such as:

- How to use MBSE-methods and tools in eco-systems of cooperating partners (supply chains, innovation partners, service partners etc.)? How to use models as the authoritative source of truth across companies (with their own ways of adopting MBSE-methods and tools)?
- How to describe the purpose of models and model requirements? How to deal with multiple models addressing the same system quality (e.g., surrogate models, or multiple models for stakeholders with their own concerns)?
- How to create models of legacy systems, how to extract models from existing design artefacts?

Finally, ESI will propose a new study to their industrial and academic partners. This study will:

- combine the results from the running applied research projects into a consistent view on the application of MBSE in the high-tech equipment industry;
- take a broader look on the application of MBSE:
  - how to create added value with MBSE, how to make it effective and efficient and to achieve a positive return of investment?
  - what is the role of models during the full product life cycle, and do we have a corresponding model life cycle?
  - what are the core domain concepts and semantics (ontology) to drive the model architecture and distribution in the high-tech equipment industry?
  - how to organize the models over the life cycle (model management)? How to combine multiple models?
  - how to organize the governance of models across the organization?
  - how to effectively exchange models throughout the value chain (with innovation partners, with supply chain partners, with other disciplines etc.)?
- dive deeper into the pilots of ESI’s industry partners
- set up an international network of industrial MBSE practitioners (beyond the network of ESI) to exchange industrial experiences, best practices, pitfalls etc.
- build a network of international academic researchers on model-based systems engineering.

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