

How to increase the MBSE Capability to enable your Digital Journey

based on the experience of leading companies in
their respective industries.

MBSE Forum is proud to present a white paper authored by a group of senior engineers and product developers who together form a growing community. This initiative brings together some of Sweden's most experienced modelers and developers, representing a wide range of industries and decades of hands-on experience in complex product development. The paper reflects our collective insights gained through long-term participation in improvement initiatives and practical implementation of MBSE strategies.

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Reading Instructions

Do you experience that demand of speed is increasing in product development? Are the expected outcomes becoming more complicated to grasp? Are disruptive changes closing in? Do you want to be on par with the drives of digitalization e.g. Digital Twin, digital thread or digital fabric? If the answer is yes to any of the questions you have the perfect reading right before your eyes. MBSE as a method for product development is a way forward to handle all the above. If the answer is no, relax, you still have time before you read, if you are not curious of course.

As usual in this type of writing, there are lots of complicated words and abbreviations. But don't worry, at the end of this paper you will find definitions and explanations for these, as well as a list of all references.

	Part 0 Why this White Paper	Part 1 The Need for Change	Part 2 How to establish your MBSE Capability	Part 3 Reaping the Benefits
	Presents the Business Values, Stakeholders, Key Messages and Reading Instructions. (also the background and history of the development of the WP)	Describes the changing context for System and Product Development and Lifecycle Management and how MBSE integrates with and supports the business operations and digital transformation.	Proposes a way forward to define and create a MBSE capability tailored to the needs of the enterprise.	Presents the benefits that can be achieved by implementing MBSE. Pitfalls and Tips and tricks are also presented.
MBSE Practitioner	Glance	Recap	Important	Good to know
Product Developer	Glance	Need to read	Important	Important
Line Manager	Need to read	Need to read	Need to read	Important
Executive	Need to read	Good to know	Glance	Important
IT / Information Manager	Glance	Important	Need to read	Good to know

Figure 1. Reading instructions

Executive Summary

In today's competitive environment, product development is under pressure from all sides: shorter timelines, rising complexity, shifting customer expectations, and the accelerating demands of digital transformation. Model-Based Systems Engineering (MBSE) is emerging as a critical capability to meet these challenges head-on—uniting technical disciplines, enabling business agility, and creating a solid foundation for future-proof decision-making.

Model-Based Systems Engineering (MBSE) as a method allows an organization to consistently use an agreed terminology for similar concepts without needing to synchronize first. This approach provides a reliable foundation for decision-making and simplifies the improvement of processes needed for deliveries. In short, it enables high-speed product development. When system perspectives are systematically covered it is easier to achieve efficient product structures and modular setups. A key advantage of MBSE methods is that they enhance enterprise knowledge management, facilitating true digitalization.

Modeling is already used to visualize and communicate in complex environments. The last 10 years have brought a sharp increase in the use of MBSE as part of the general trend of Digital Engineering. Although many companies are attracted by the benefits shown by those that have succeeded in their adoption of MBSE, few have managed the transition effectively. This white paper aims to guide on how to increase an organization's MBSE capability based on the experience of companies in different industries who have successfully adopted MBSE to some degree. It also attempts to provide practical insights and reflections to those that want to build an MBSE capability and turn complexity into a business advantage.

Systems Thinking is so far the only established way to manage complexity based on scientific principles. The frontline of managing complex information is presented by the domain MBSE which combines traditional systems expertise with principles for managing knowledge. This connects information in an unprecedented manner. Unfortunately, MBSE itself is associated with a set of presuppositions which risks naive decisions in search of simplicity which do not meet the needs and demands of reality. Most development companies that conduct complex product development have senior product developers knowing which perspectives are most important and which systems aspects that are needed to cover the perspectives. The demands of rapid product development is one of the key driving factors in the search for simple answers to questions in complex environments. If an organization wants an effective base for taking decisions, they need a product centric way of work allowing the decisions to be based on product centric information in relation to business driving perspectives. This is what MBSE is all about. If an organization wants to unlock the intrinsic motivation of developers across solutions and technical domains, a product centric information management, in an MBSE setup is essential. MBSE represents method which can be compared to the use of map and compass used in orienteering. Trying to find a way through a piece of land on a big scale requires that teams use the same type of references as a map and compass if they are to

communicate effectively. If you are not using a common method (MBSE set-up) in the digital future that is comparable to a situation where all your teams (with actual manning) would be travelling across a country with different navigation tools like map types with different resolution and different types of compass measures. The teams would continuously need to communicate a lot just to be able to communicate at all with accuracy, especially since the terrain in a company competitive environment continuously changes.

Any significant change in methods used for Product Development must be harmonized with strategies defined by the enterprise. In publicly held enterprises the strategies are issued by the board, and these represents what the shareholders are in favor of. Executive boards are active with plausible divestment, financial risk management, social virtues and environmental or governing (ESG) strategies. If shareholders' strategies are not aligned with stakeholder needs, there is a risk of losing control. Establishing transparency and clarity in potential conflicting strategies is advised. Product as a Service heavily relies on Stakeholder needs. Shareholders priorities and stakeholder priorities must be both clear and synchronized for optimum effect for all enterprises, small or big, for not losing product value itself.

MBSE is an exhaustive method most inclusive to multiple considerations, including different shareholders' concerns, and can be a well-balanced tool for strategic decisions. The systems theory of considering both shareholders and a multiplicity of stakeholders is unprecedented in its systematic approach. MBSE is to be seen as an excellent mitigation strategy to a largely more Volatile, Uncertain, Complex and Ambiguous world (VUCA-world).

Our society and the products become increasingly complex due to higher level of connectedness and integration in combination with expected seamless functionality.

This paper is authored by some of the most experienced and senior product developers and modelers in Sweden. Representing complex product development, the authors have had the opportunity to work on complete product perspectives taking in stakeholders account in the actual end user products for several decades. The authors have worked on wholeness over so long time that first-hand experience has been enabled by participation in many improvement initiatives e.g. 50-50, Kaizen, 6Sigma, Lean, Agile and Digitalization. All initiatives have brought something useful to the continuation of work. Yet, MBSE as a methodology has not yet been critical enough to be fully embraced by most product development practices. With the emergence and criticality of the first questions in this summary, a fully integrated and balanced MBSE capability is needed, see Part 2 - How to establish your MBSE Capability. If you want your enterprise to be a part of the digital future an established MBSE practice is now a "must have" and not a "nice to have" anymore.

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Part 0 - Why this White Paper

Background

The objective of this White Paper is to offer guidance for enhancing an organization’s Model-Based Systems Engineering (MBSE) capability. It is based on the practical experience of companies, leading in their respective industries, who have increased their MBSE capability significantly. One of the main drivers for promoting MBSE is to enable knowledge sharing and unleash the speed inherent in the organization by clarifying driving perspectives and values. MBSE can be considered a method or technique to make the Data-Information-Knowledge-Wisdom pyramid, Figure 2 , salient in an organization. The more wisdom afforded by managed knowledge the less risk and cost is related to important decisions. MBSE as a method will bring the value of order and stable bases for product centric decision making associated with less risks.

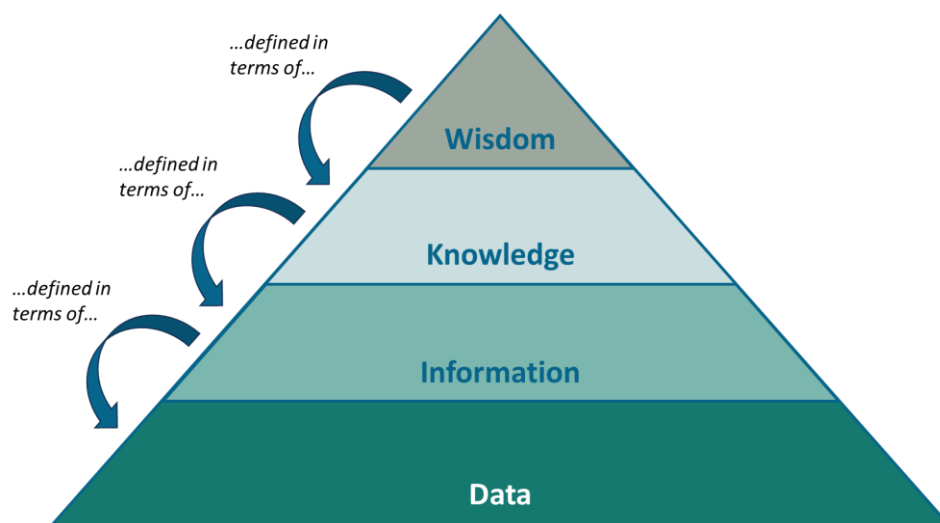


Figure 2. Interpretation of the Data-Information-Knowledge-Wisdom Pyramid based on [1]

When Data and Information is mentioned, it inevitably leads to the currently ongoing digitalization, which is about marrying traditional Information Technology (IT) and Operational Technology (OT). A prerequisite for success in this is to get these disciplines to work together and that is only possible if we have a common vocabulary and conceptual models that rely on standards. Therefore, the nomenclature in this paper is aligned with the ongoing work within Smart Manufacturing ISO/IEC JWG21, where a common Reference Model is developed as a framework for the standard, IEC/ISO 63339 Unified reference Model for Smart Manufacturing, URMSM [2]. The Scandinavian Smart Industry Framework, SSIF, has published a Technical Report, SIS/TR 66:2023 TK 280 by SIS TK280, which links several international framework initiatives as input for JWG21, see Figure 3. SIS TK280 Team has presented how propositions from IEC/ISO 63339 and principles also works in reality by test cases at Volvo Cars, Saab Kockums and US NIST (Additive Manufacturing).

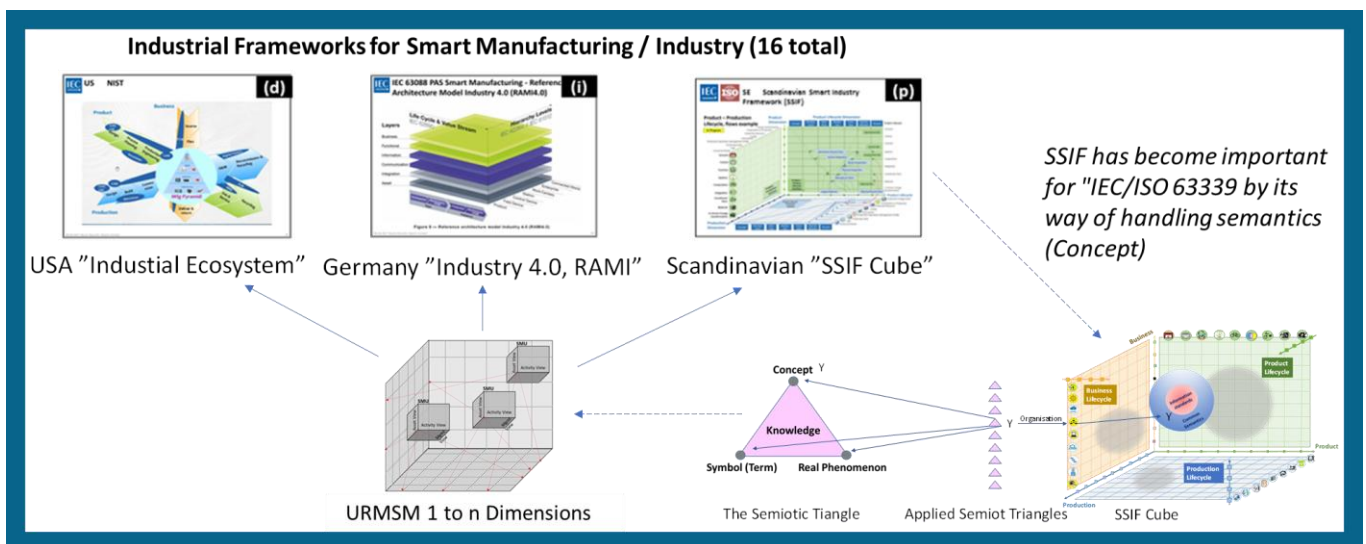


Figure 3 – Different proposed frameworks merged into URMSM.

Short definition of MBSE

MBSE is a method that is built on the practice of systems engineering where you develop and use system models to support both development and management of a system. System models are in MBSE a set of representations gathering information which needs to be aligned for the business to thrive, and which needs to be managed together by the different engineering disciplines under the system's life cycles. As an example, MBSE could enable efficient Requirements Management, System Design and Analysis as well as provide a basis for Development, Verification and Validation and Configuration Management. It is not by coincidence that MBSE is the essential enabler for defining the Solution Intent in SAFe, Scaled Agile Framework [3].

System models describe a system's elements, its structure, relations and behavior. These models are intended to be used as the de facto source of information enabling communication between different disciplines.

A model-based set up is a prerequisite to meet future challenges of complexity and for enabling digitalization. Managing and updating information in models is more efficient than working document centric and continuously updating documents with many relationships. With a model-based set-up the mastering of data becomes more explicit and by that changes that affect different perspectives can be centrally changed which saves time. Today there is a demand for product development to be fast, and it is not expected to slow down even though developed products and systems become more complex. Complexity increases with new business challenges to keep up both with expectancies of time-to-market, global teams and evolving needs from the customers. How emerging complexity feeds into one another is exemplified in the Figure 4 below.

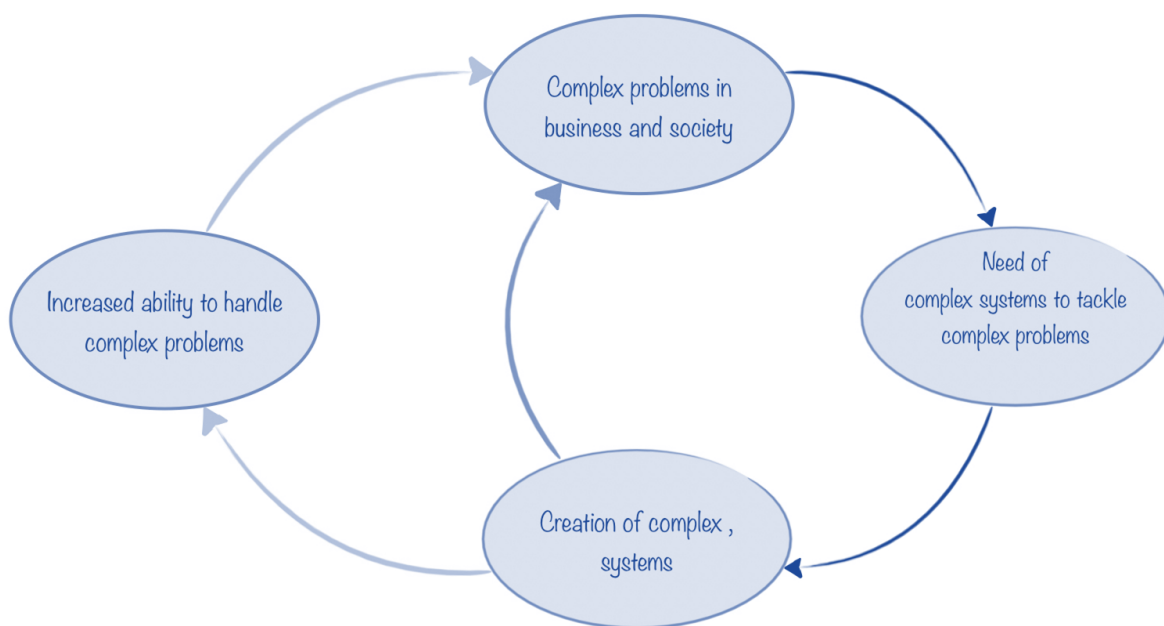


Figure 4. Complexity dynamics. (Source: adapted from [4])

A prerequisite to model systems in a consistent way is a common vocabulary. In System Engineering the standard ISO/IEC/IEEE 15288 provides a foundation but this normally needs to be accompanied by domain specific languages (ontologies) to be applicable across stakeholders both within and between different teams. By combining the ISO/IEC/IEEE 15288 with a common reference model like e.g. the Unified Reference Model for Smart Manufacturing provided by ISO/IEC 63339 the prerequisites for efficient company internal data management as well as cross company collaboration with different tools can be strengthened. [5]

Perspectives of MBSE

In a work by fellows of INCOSE seven different worldviews of “a system” were defined [6]. Depending on the world view taken, a system might mean different things and consequently MBSE will potentially have different scope and meaning to the reader depending on the actual perspective. But no matter if the engineers adhere to the definition that a system is an abstract construct or a physical real-world thing, MBSE helps in organizing systems. Regardless of how the company has defined the product under development the MBSE approach based on systems thinking will help in organizing entities with clear definitions, boundaries and intra-relations (interfaces).

In this paper the broadest world view, that everything can be a system, is the base. The views is further detailed by two main perspectives of the system as either of interest from the “*Engineering perspective*” or from the “*Enterprise perspective*”. “Enterprise” here is defined as a project or undertaking of a defined business goal, i.e. it is not just the representation of a large international company. Even small companies or expeditions are conceived as an enterprise.

Engineering perspective

In this perspective the values of system modelling from an engineering perspective are in focus. This is the most used view when talking about MBSE. The purpose of this perspective is to gather, structure and visualize engineering specifics of a product as the System-of-Interest in a model, e.g. requirements, use cases, logical and physical architectures, etc. Here the System model is one of several parallel engineering models, such as 3D models, simulation models and virtual manufacturing models, etc. Interaction and information transferred between the models exists today but are often managed manually, and this is one of the digital challenges to start to automate and create bigger common views of the product across traditional disciplines and engineering dimensions.

Enterprise perspective

In this perspective the different parallel models from the *Engineering perspective* are used in the wider Enterprise context and merged with models from other aspects of the enterprise like Finance or Marketing. For transparency, traceability and efficiency purposes, the models need to be digitally interlinked and collaborate as changes in one model will potentially affect other models. Managing this manually can be done but will introduce both risk for manual errors with related consequences but most certainly escalates cost due to increased process needs (manpower and time to market). The *Enterprise perspective* merges all valuable models in the enterprise by connecting items/objects with dependencies from different dimensions into one coherent digital thread.

In an MBSE context, it is important to clearly distinguish between problems and solutions at both the enterprise and system levels. This clarity helps prevent misalignment between strategic objectives and system capabilities. A problem, maybe found when seeking an opportunity, is a challenge or obstacle that hinders obtaining goals. This can occur at both enterprise level and system level. A solution is the action or strategy to address these problems:

- at the system level, it often entails technical design or updates.
- at the enterprise level, it might involve organizational changes or adopting new business models.

Understanding the scale and context of the problem is key to crafting an effective solution through all perspectives. In Figure 5 a reference model that addresses this is presented. It will be further detailed in the section Information Architecture

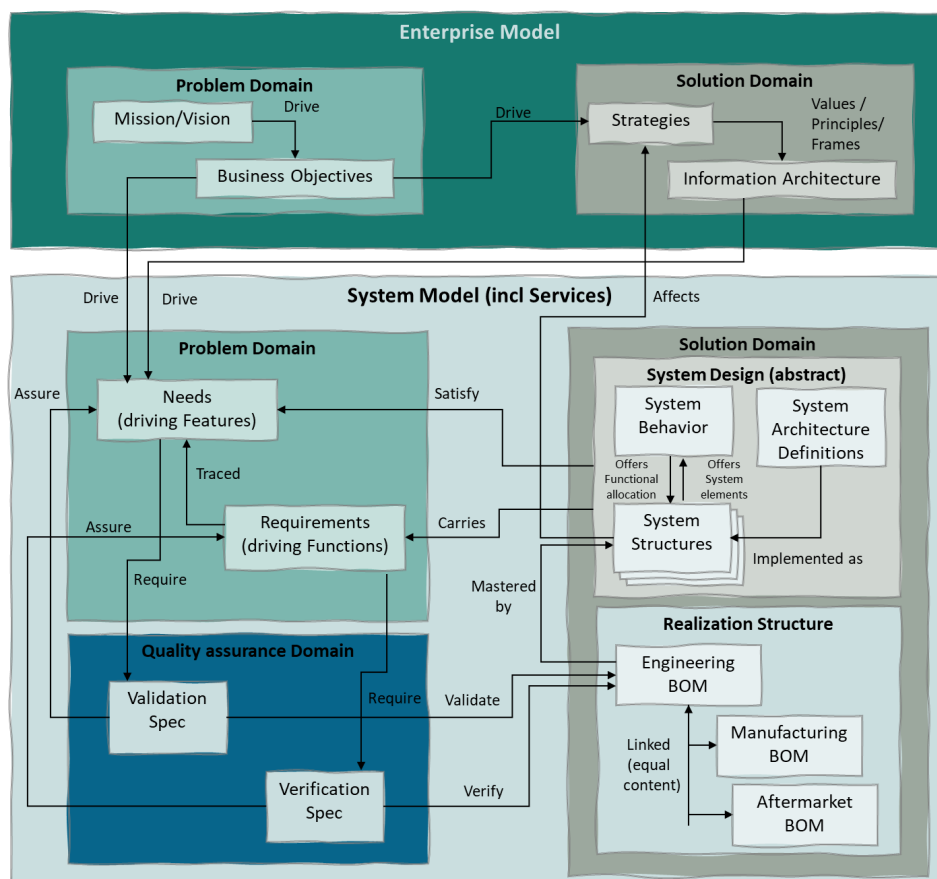


Figure 5. The conceptual System model in enterprise context

See the image of our reference model as a concept of possible interesting domains, not realized objects. Only a subset of the content per domain is represented.

Part 1 - The Disruptive Change

Changing context

MBSE enables a shift from document-centric work to a model-based setup enabling digitalization e.g. advocated by Industry 4.0. An example of what Industry 4.0 means is presented as technical trends and design principles below [7].

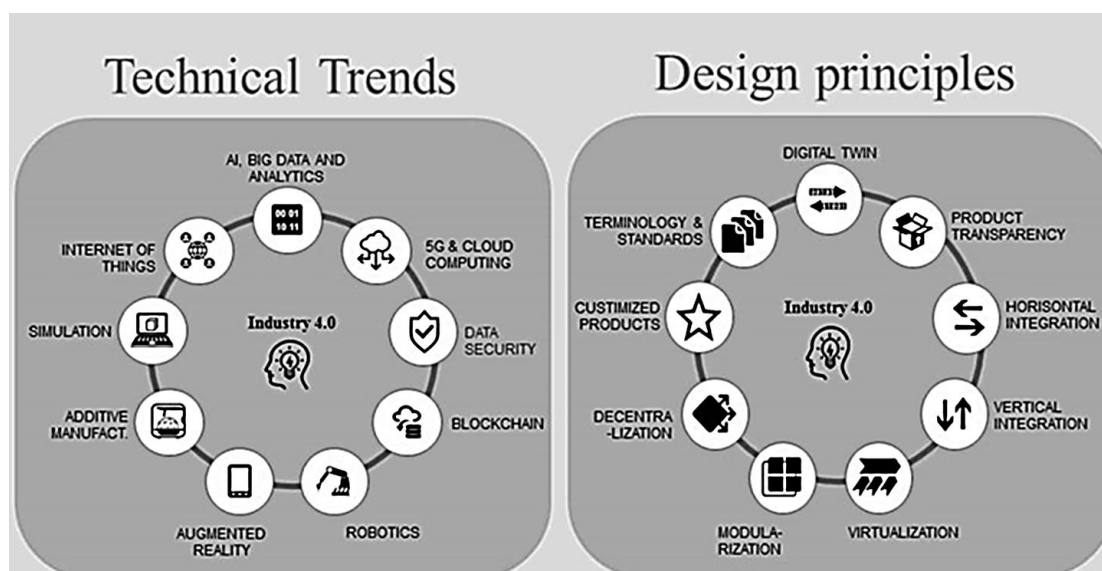


Figure 6. Response to Industry 4.0

New demands can be perceived as complex and/or ambiguous due to the increased need for cooperation between enterprise and engineering domains. Organizing the information in System models brings value through increased clarity in communication in the product development context. Organizing information in a systematic way also enables an increase of speed and quality at the same time as continuous improvement for both products and processes. A scattered information landscape will continuously impose heavier burdens of synchronization and re-use of effective patterns, and heuristics will not be as efficient. The companies that organize themselves the most flexible and yet efficient will thrive the most, this is what MBSE is all about. MBSE is a method to align design principles presented in Figure 6 to meet the technical trends in a controlled manner.

MBSE, Desired State

The value proposition of using MBSE is the enabled speed and clarity in communication between different stakeholders. It enables product development to do the right thing in the right way for both top-down and bottom-up changes and can be seen as a bridge between Engineering Perspective and Enterprise Perspective. Principles used in MBSE encapsulate structures used in different methods and processes into something that is defined and structured, providing a systemic approach based on systems thinking and systems science on how to build and use models. MBSE provides methods to create the connective tissue in an enterprise's digital product environment, a conceptual representation is found in Figure 7.

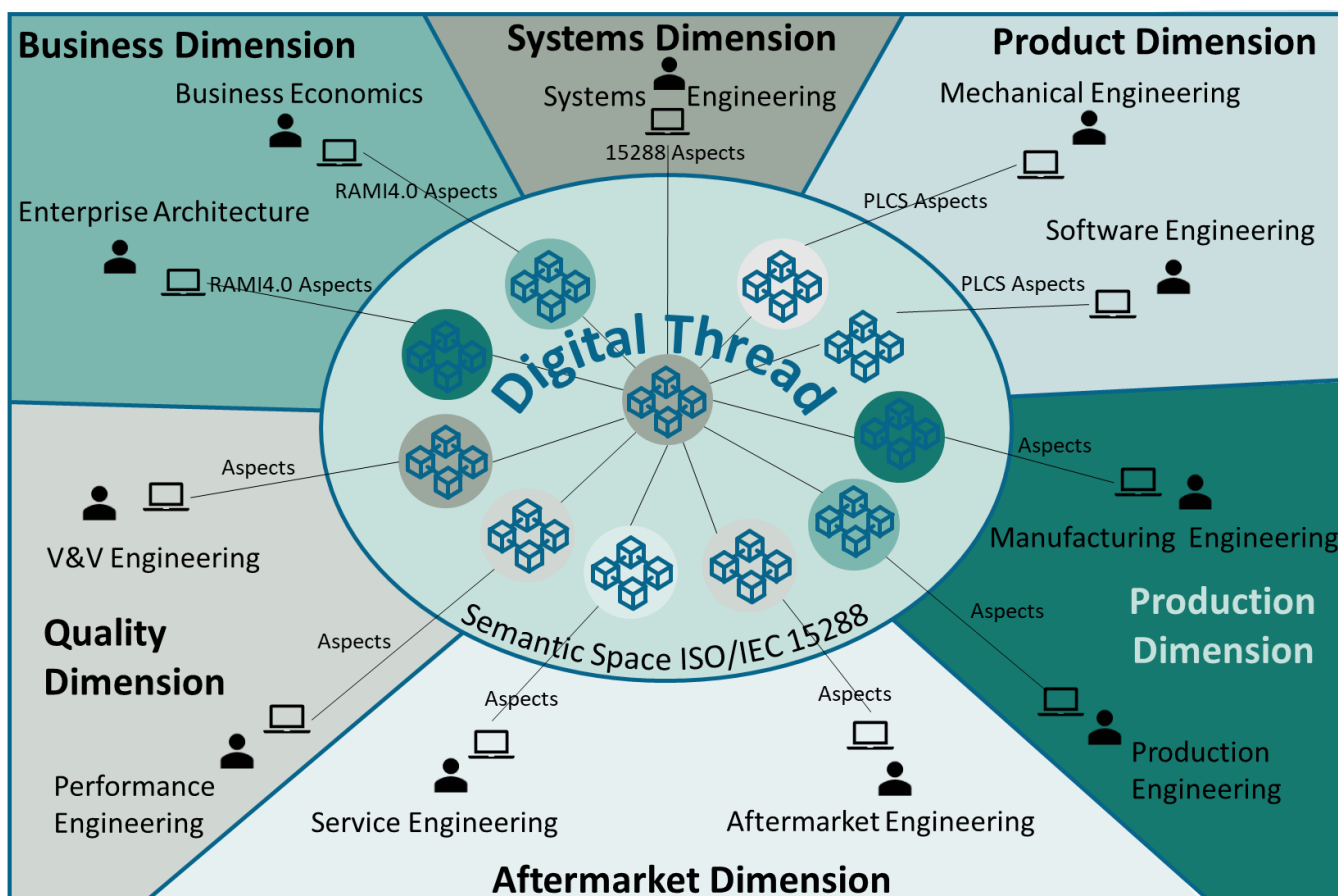


Figure 7. A conceptual representation of MBSE as the connective tissue in an enterprise's digital product environment. With definitions from IEC/AWI 63339 Unified reference Model for Smart Manufacturing.

Today, with fast changes of information there is a risk of gaps between what manufacturing companies envisage on a strategy level based on market needs and how the solution is realized by engineers from different disciplines. When the stage of testing and integration starts it is often discovered that certain systems do not cooperate with others, it may not fulfil the customer or the business needs, or a market disruptor has emerged rendering the development obsolete because of long development cycles. If this sounds familiar, then it could suggest that such a gap exists in your organization and MBSE could be a solution to bridge that gap.

While an enterprise information landscape represents how the organization should align with the business strategy and goals, it is most often not presenting details on how the execution or work in progress looks like. MBSE covers methods to align the different product development lifecycles via a central system representation. This improves the understanding and efficiency between engineering disciplines at every life cycle stage, ensures a higher quality product through early fault detection and consistency, significantly lowers the need for rework, and reduces the development risk by enabling earlier impact analysis on changes and improved verification and validation. By taking a model-based approach using the system model as the authoritative source of truth and its contained information to drive development, the enterprise will by default have achieved a digital solution platform which can be used across the enterprise, Figure 7. MBSE is essential for documenting large amounts of knowledge and is very supportive in visualizations of lifecycle aspects of the Systems through the whole product life cycle.

MBSE can also be seen as an enabler and essential steppingstone in continuous improvement. Many products are evolving into smart products with a continued exponential growth in functionality and without proper methods and tools to manage your products throughout the entire lifecycle, it is very easy for your product to get out of hand.

Still too Abstract?

If MBSE still seems too abstract of a subject, and who the beneficiary might be from such a transition, an example would be to liken it to the huge shift during the 90s when the transition from 2D designs(drawings) into 3D models was made. This is similar in comparison to what we want to achieve today with MBSE, where the transition should be from documents-based SE, or silo managed data, to model-based SE. Today nobody questions the use of 3D models, but of course the transition to it was not straight forward. In this perspective we now understand that this kind of transitions needs to affect the complete organisation of an enterprise to bring value. The model itself will not bring value, it is when we can use and reuse it. When the transition is done the system model will be the unifying platform for all decisions in Product Development.

Examples where MBSE is a desirable enabler:

MBSE is primarily a product development methodology, a way of working and a problem-solving mindset for development of new products and services (Greenfield Engineering) or for incremental improvements on already existing products or services (Brownfield Engineering).

Product development is about understanding stakeholder needs and what the customer might be willing to pay for. Speed in execution within development cannot be regarded as a “flow”-problem and there’s nothing repetitive about it. It’s a “finding-out-endeavour”.

No project endeavor is alike, the same techniques or strategies to increase effectiveness in manufacturing (split/reductionism, repetition, scale, flow etc.) can’t be used to increase speed in product development. In product development it starts with understanding the bigger and wider picture to enable conceptualization and putting the new product in perspective (or context). It is necessary to truly understand what is required and expected from the novel product. The Synthesis of a Product and/or Service/s is within development known as the ‘System’. The term Synthesis stems from ‘Systems Thinking’ and is called ‘Systems Engineering Method’ when applied to Product Development, thus enabling efficiency by Concurrent Engineering or Agile release trains.

Synthesis is a means to abstract away from legacy designs and make it possible to truly enable and identify new innovative solutions. The opposing strategy is to work bottom-up, starting with available parts and how they can be improved separately or reconfigured into new products. Instead of polarizing between the two perspectives MBSE allows for both.

The major challenge, in order to understand and obtain MBSE capabilities, is moving away from the thought of a continuous improvement of already existing products. There’s nothing continuous and repetitive about Product Development. Continuously evolving and adding options and improvements to a product puts you at risk of introducing a technical debt, where the design becomes detached from the desire and needs of the customer. Each new product starts with understanding the full context of its intended use and exploring the market opportunities, i.e. a Systems Engineering approach. We acknowledge the market is constantly changing and the business opportunities always need to be analysed to keep up with the competition. It may seem more effective to slightly improve the existing product. You may very well end up with a new product seemingly evolved from the legacy product, but there’s nothing evolutionary about the pathway to that new product. Organisations embracing the ideas of System Engineering are likely to succeed with innovative designs.

More specifically MBSE is about creating system models based on interconnected views capturing what the System or Service is expected to do and how to behave. Once integrated the system model comprises the formal problem definition and system design solution.

“A Problem Well-stated is Half-solved”

[Charles Kettering](#) [17]

Within the System Model, the Systems Architecture of the new product is established using trade-offs and careful orchestration of what technologies are best suited to solve a particular problem. Many organizations have architectural patterns constraining the new product, these are also considered in doing the Systems Architecture amongst all other behavior, safety, quality and performance aspects needed to be considered.

In developing Complex Systems, the number of considerations needed by far exceeds what is possible to capture in documents. By the clever use of Models, we are today able to formally capture and maintain (over the entire lifecycle) the information and knowledge that goes into developing a Product. This knowledge is very valuable.

Much like the success of going from 2D-drawings to 3D-CAD models, the MBSE system models are also open for extensions and additional valuable usages of different models within the Engineering perspective. Where 3D-CAD models today are heavily used to do kinematic analysis, CAE-simulations (incl. FEM), Digital & Additive Manufacturing etc., system-modelling supports Digital Twin, Analytics, Machine Learning, Variability Modeling, System-of-Systems, Virtual Verification & Validation, System Design Thinking, Product Line Engineering (including Configuration Management), Scaled Agile and Product-Service Systems.

These are all areas spawned or enabled by MBSE and tend to be highly desirable by many organizations. None of them are viable without first mastering MBSE. Figure 8 below presents examples of popular business initiative where MBSE is a desirable enabler. These are elaborated in the following sections.

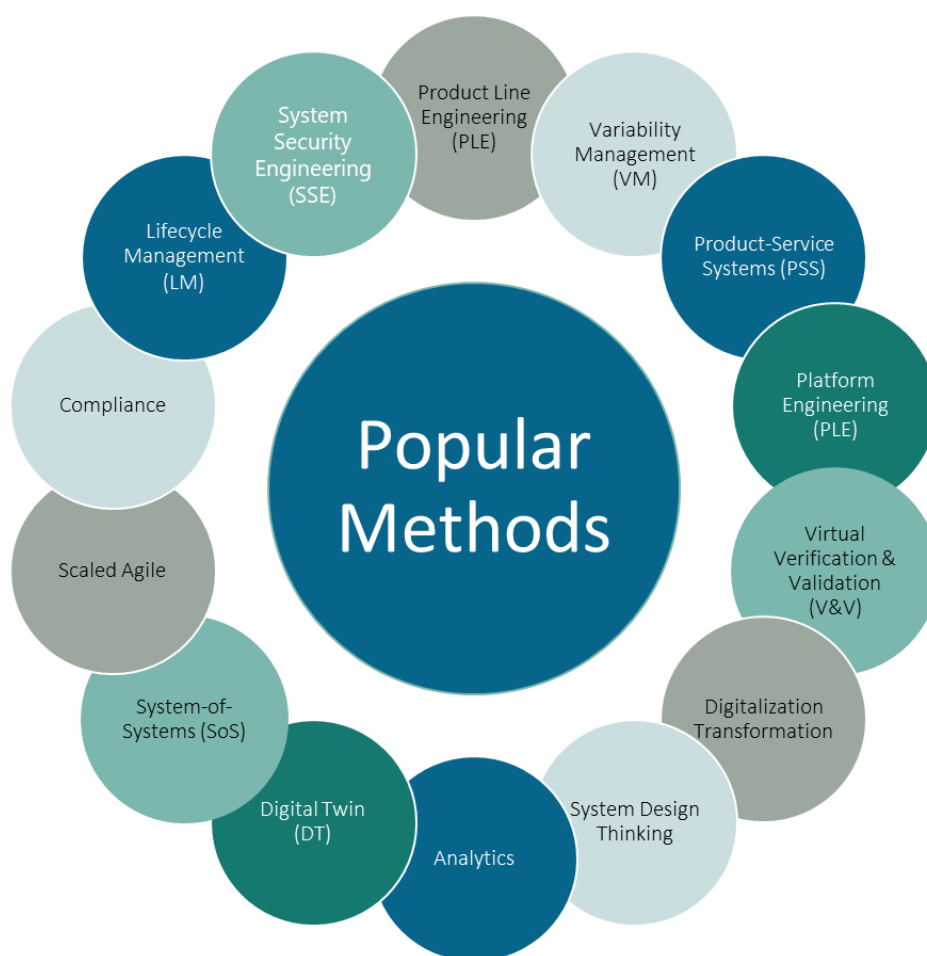


Figure 8. MBSE is an enabler for other business objectives and initiatives.

1. Product Line Engineering and MBSE

When developing many similar products there are synergies to harvest amongst product members within a Product family (Product Line/Platform). The reusable assets can be of both physical and digital nature. With a few extensions to MBSE (e.g., Variability Management) we enable harvesting synergies also in Specifications, Functionality, Test Cases and even leveraging on Test results amongst product members. The magnitude of reuse in this area is often more lucrative than reusing the physical parts themselves. When MBSE is extended with product line support, we refer to it as MBPLE. MBPLE supports anticipated and opportunistic reuse by use of variations amongst product members.

2. Variability Management and MBSE

Attempting to manage variable products in over-specified bill of materials (BoM's), is often very limiting. Even when utilizing more advanced configurators, there's a limit to what can be done. The trick here is to shift focus from *the Solution Space* and instead attribute *the Problem Space* with variability, Figure 9 (*Problem Space* here corresponds with the System model except for the Realization Structure in the Reference model in Figure 5). The Solution (CAD files and Software binaries) is then bonded to the problem. This can be accomplished by an MBSE tool suite where traditional SE and PLM are aligned. Variability is dependent on context where Feature Models are used to extend the System model and Variation Points are assigned to the diagrams. There are today numerous formal modeling languages to do this using international standards.

Remember; it's not solely the Solution that varies. The problem (features, functions, performance, quality attributes, test cases etc.) varies for different markets often differently from how the solution varies. Configurators with include/exclude rules are insufficient, what is needed is proper Variability Management [8] to account for all variations (including also Services and Source code).

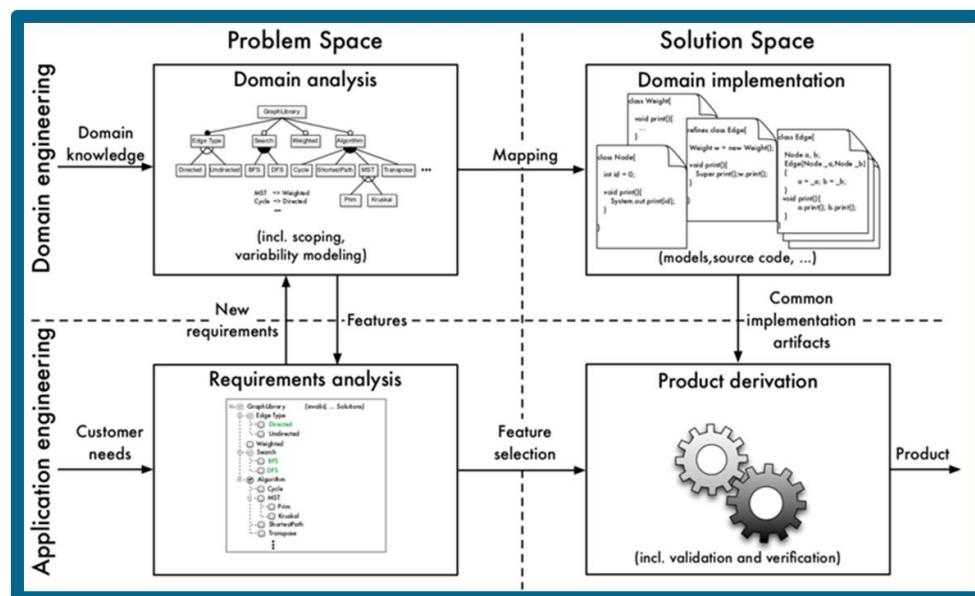


Figure 9 Illustration of how individual parts and source code is bonded/mapped to the definition of the problem according to the standard ISO/IEC 26557:2013. Instead of attributing individual parts with more information, the 'Problem' varies (defined by variation points captured in a variability model).

(Source: adapted from [9])

3. Product-Service Systems (PSS) and MBSE

In the Services economy, the methodology called design thinking is advocated. This is an approach that is more user-centered, experience-focused, more agile and iterative. It is more holistic in considerations of stakeholders as well as more collaborative as it cuts across traditional domains. Under the service paradigm design is no longer just about products (or services), now we need to also design actions and processes in conjunction with our more traditional product features. The Services provided is likely to be context dependent and thus introduce additional complexity with regards to variability. The Services will be dependent on the Product Features, and the Products will have a strong dependency on the Services offered. Even though Service Oriented Architecture (SOA) patterns are deployed, there will be strong dependencies regarding lifecycle aspects to be managed amongst constituent Systems and Services. To formally manage dependencies, modeling of these Systems or System-of-Systems will become essential.

4. Platform Engineering & MBSE

Often organizations rely on various technology/domain-platforms created in preparations before Product Development commences. Unfortunately, this tends to isolate engineers into their “stovepipes”. Once the domain platforms grow in complexity, they become more detached from their final context of use [10]. MBSE instead deals with this by focusing on *Product* Platforms (combinations of technical domains). Instead of creating generic hardware modules and software platforms we would see domain cutting solutions more tailored for a particular range of products (where the synergies are the most). Such cross-cutting platforms are always designed for a (anticipated & dedicated) purpose in mind.

5. Virtual Verification & Validation and MBSE

When V and V is discussed, the work is frequently stopped when a consensus of how to define the two terms is reached. It is seldom continued to the point of discussing how to validate *a Problem*. It is common to talk about validating *the Solution* using customer clinics and acceptance tests. Often flaws in new solutions can be attributed to the developing organization’s lack of full understanding of the problem. Even if work strives to become more iterative and fast-cycled by redesigning the solution. It is always faster and cheaper to make sure we understood the Problem correctly. MBSE utilizes simulations in combination with the problem definition to accomplish agile and iterative early validation.

Organizations, mature and skilled, in MBSE reiterate the Problem or opportunity until it becomes the Solution, instead of iterating a Solution until it is viable, or the time runs out and the solution will be verified and validated on the *field*.

6. MBSE in Digitalization Transformation (“Enterprise Engineering - MBEE”)

Often MBSE methodology is applied to product development initiatives when considerations and dependencies become overwhelming. MBSE is however not limited to developed man-made physical systems. In digital transformation, organizational and enterprise structures often need to be reconsidered. How an organization operates can easily become equally (if not more) complex and can sometimes be difficult to improve upon. MBSE has proven to be a valuable tool in supporting Organizations to manage the digital transformation of the company [11].

7. System Design Thinking and MBSE

A System doesn’t only exist in the Solution Space, a ‘System’ is an abstract term also used within the Problem Space, Figure 9. Often the term System is used in naming a Solution (e.g. exhaust system) which over time increases the association to “real” systems although a system in MBSE can be totally abstract. Much like ‘Function’, which also is an abstract term not used in PLM (solution) although it is a vital item for defining a problem. System Design consequently is an abstract way of designing without details (i.e., No detailed CAD illustrations needed, aka “High Level Design”).

8. Analytics and MBSE

Analytics is an emerging discipline in Engineering of Systems. By iterative agile modeling/simulation loops (e.g., Monte Carlo-simulations) in the problem definition, vast amounts of data are analyzed to find the best trade-offs and requirements parameters for downstream design work. Systems Design is refined using analytics and simultaneously validating System Design (in the Problem Space, Figure 9).

If this approach is extended to include real data from products in the field, understanding of how a Digital Twin emerges, it could be helpful in making better design choices.

This also means that monitoring of any data points is enabled, without including other logs in the actual product. The Digital Twin is given more in-depth analytics possibilities than the actual product AND can be complemented with actual data from machines when needed.

9. Digital Twin and MBSE

A Digital Twin is a digital counterpart of an actual product (individual, type or service). But it's not as simple as only having a digital list of things comprising your product. That would constitute a digital representation, not a Digital Twin. What constitutes a Twin is dependent on what the intention with it is. If the intention is to use it in several different areas, it can be worth considering having multiple Digital Twins.

In its simplest form it would render an identical physical replica of the actual product and make sure the replica is subject to the same wear and tear to the product sold. This is, however, not very practical. Instead, a digital corresponding model is created of a product, it is expected to behave the same way as the physical counterpart in all essential regards. This allows querying and analysis without having to go to the actual thing. At best it is possible to use and abuse the Digital Twin beyond what is possible with the physical original. It is possible to make predictions and to simulate scenarios using the digital twin. There are defined levels of Digital Twins ranging from the simplest to the more advanced usages requiring a more sophisticated model. Even the basic Digital Twin concept includes a System-model that could provide a logical output/response. Digital Twin concepts are also addressed solely from a simulation perspective, but to become a viable and sustainable part of the baseline of product, it needs to be included in the "digital thread".

10. System-of-Systems and MBSE

Systems and Services are becoming more inclusive and integral. The emergence of cooperating products and new business models calls for new ways of working. Liability and warranty issues are becoming illusive in systems comprising many constituent products. AirBnB, Über and Autonomous transport solutions are examples of System-of-Systems (SoS).

MBSE accommodates this new paradigm and scales modeling using standardized frameworks like TOGAF, MODAF and UAF. SoS is per definition made up of many constituent Systems considered to be operationally independent and that each have a lifecycle of their own. Constituent Systems may have other purposes and features not included in what is accomplished when cooperating. When modeling this vast SoS Constituent Systems can be treated as a Services (e.g., The excavator performs 'a Service' of loading the Hauler on a construction site). When modeling SoS systems it is therefore essential that we model Product & Services together. When external constituent Systems are included, we make use of the System models to get the full understanding of the whole SoS.

11. Scaled Agile and MBSE

It is often believed Agile ways of working exclude the need for Requirements and proper Product Definitions before Detailed design work is performed. This paper indicated that agile ideas are equally applicable to the problem domain. Very often the agile ideas are applied in the design arena but neglected in Problem Definition and Early phases. This is also a common cause to why scaled agile initiatives are challenging. Scaled agile initiative are very inclusive and recognizes the use of MBSE and in developing complex machinery and services, MBSE is an essential part and enabler in Scaled Agile. Continuously iterating a solution without revisiting the problem definition will rapidly induce a technical debt and make any used models out of date. In worst case existing set-ups (models) can even become implicitly obsolete.

12. Compliance and MBSE

Many Systems and Services are developed in highly regulated markets. Regulated markets are accessible through certification by authorized bodies demanding certificates or proof of accreditation, technical files and adherence to quality assured processes. Unless you're in a very deterministic industry domain, where all essential technical properties are already determined, you need to be able to derive what has been done to avoid hazards or foreseeable misuse. Through MBSE with its various lifecycle perspectives, it is possible to create a trace or thread providing and maintaining the validity of this argument.

13. Lifecycle Management and MBSE

Product Lifecycle Management (PLM) and Enterprise Resource Planning (ERP) together constitute support for establishing 3 essential lifecycle perspectives (Engineering, Service & Operations and Manufacturing & Supply Chain). Lifecycles where Features, Functions, transport, commissioning, decommissioning, refurbishment, and complementary structures where Services are made tangible are missing. MBSE provides the opportunity to explicitly establish essential viewpoints for these Lifecycle perspectives, making the Product Baseline complete, consistent and coherent (C³). Accommodating for all life cycles is essential in developing complex compliant safety critical systems on highly regulated markets. Being able to capture structures relevant for all identified Lifecycles constitute the base for a digital thread, traceability, knowledge management and constitute a good start for a Digital Twin.

14. System Security Engineering - SSE

Security is increasingly becoming more important and an integral property of our Systems. A Cyber Secure System is not something accomplished by patching existing Systems, or something that can be bolted on retrospectively. Like many other quality attributes and properties, it has to be considered from the start. A secure system is likely to have an impact on the core architecture and must be documented alongside many other aspects of our system in order to be maintained throughout the expected lifetime. SysML can be used alone or in conjunction with more dedicated Security languages and viewpoints in MBSE to secure security (pun intended).

Part 2 - How to establish your MBSE Capability

Defining an MBSE Capability

To scope the ability to do systems engineering effectively in a model-based fashion a capability model is defined. The MBSE capability model recognizes that MBSE is conducted in an enterprise context and the level of the MBSE capability must be balanced to other needs and preconditions to the enterprise in terms of business, architecture & product, process as well as organizational factors (the enterprise context), see Figure 10. For example, the desired level of capability is different if the enterprise needs to deal with a “simple” versus a “complex” product. Hence, the recipe for establishing an MBSE capability might look different between enterprises.

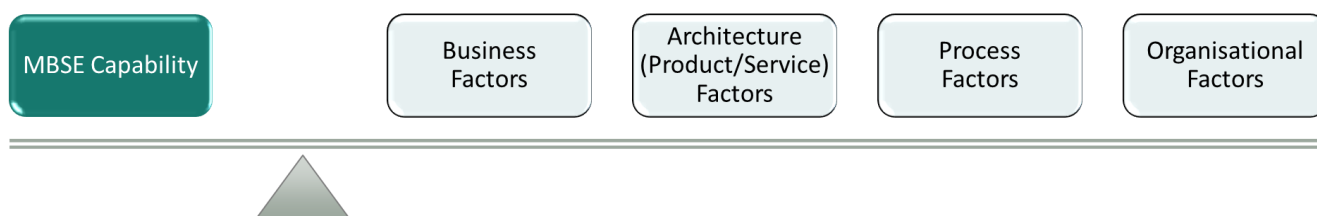


Figure 10 –The MBSE Capability balanced against other factors in the Enterprise context.

This means that it is necessary to up-front consider a set of context factors to define relevant MBSE capabilities and goals that are on par with what the enterprise can engage in. Examples of context factors to include can be organized using the BAPO-model [12]:

- Business Factors (B), which include for instance: Business strategy long/short-term; Market Geographical coverage; Lifecycle Coverage: Concepts/ Development/ Production/ Sales/ Operations & Service/ Disposal; Regulatory and compliance needs; and Customer Expectations & value propositions.

- Architecture (A, Product and/or Service) Factors, which include for instance: Technical complexity; Interoperability & integration; Scalability & flexibility; Major Interfaces and Operational Scenarios; and Data & Information Governance and flow structures.
- Process Factors (P), which include consideration of factors such as: Process standardization requirements vs. flexibility; Process maturity; Use of Methodologies & Best Practices; Adoption of automation; and requirements on Process documentation.
- Organizational Factors (O), which include for instance: Size and distribution of organizational units involved; Organizational culture; Roles and competencies defined; Personnel/team maturity; Multi-site coordination; Governance & decision-making; and Tool support and experience.

The Capability Model recognizes that building a lasting capability requires more than process and tools. As illustrated in Figure 11, the elements that build up the MBSE capability include Governance, Organization, Process, Process support, Information Architecture and IT support. Each of the capability elements is described more in detail after the “Steps to take” section.

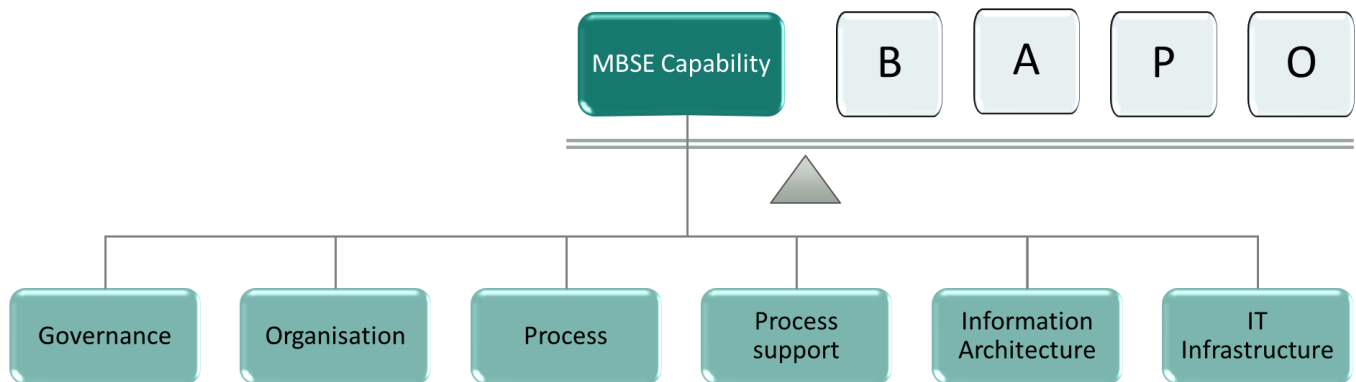


Figure 11 – The Capability model

Steps to take

The starting point is getting the mandate to engage in MBSE capability development. The capability model presented in the previous chapter provides a useful framework to manage the capability development effort. Given the mandate, the capability development is then structured into an iterative loop of four main activities: Defining the scope for analysis; performing analysis: planning implementation; and implement and follow up. The activities are underpinned by a thoroughly planned and practiced communication, see Figure 12. This paper argues that the MBSE implementation process should be iterative, starting with the most apparent needs and gradually expanding the scope.

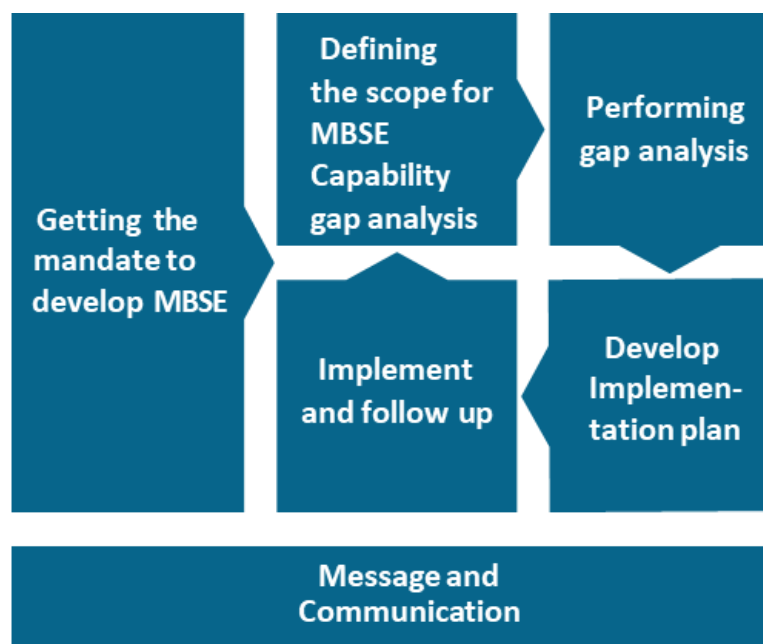


Figure 12 - Steps to take

Step 1) Getting the mandate to develop MBSE

Establishing a MBSE capability begins with obtaining a clear mandate for change. This typically depends on the organization's current maturity, readiness for transformation, and the degree of urgency that can be effectively communicated. It is recommended to identify desired improvement areas as a starting point.

To support the case for MBSE, organizations should leverage both internal drivers and external references. Internally, highlighting the benefits and the many uses of MBSE as outlined in Part 1 can help engage management. Externally, strategic references such as the INCOSE Systems Engineering Vision 2035 underscore the growing industry consensus on the value of MBSE adoption.

However, a recurring challenge is the "Catch-22" dilemma: management seeks evidence of return on investment (ROI) before committing resources, yet demonstrating ROI typically requires an initial investment in MBSE capabilities. To address this, organizations can use comparative scenario models—comparing their current MBSE maturity with envisioned future states or with successful MBSE implementations in similar industries. Supporting this with evidence from published studies, such as the defense-sector example in [13] can significantly strengthen the case.

A foundational step in securing a mandate is to clearly define the objective of the MBSE initiative. While informal leadership can direct early efforts within existing roles, sustainable progress typically requires the establishment of formal MBSE governance. Without this, structural or cultural resistance may delay meaningful change.

Business Factors must be aligned with the organization's MBSE maturity level. This requires asking, "*Where are we on the MBSE journey?*" Effective transformation depends on the coordinated engagement of three leadership dimensions:

- **Political leadership** – setting strategic direction (“what should be done”),
- **Technical leadership** – ensuring long-term effectiveness and engineering quality (“how to do the right thing right”), and
- **Executive leadership** – driving execution and delivery (“getting things done”).

Without buy-in from political leadership, even sound MBSE initiatives may stall. Alignment across this leadership trinity is crucial to build and sustain momentum toward higher levels of MBSE maturity.

An essential output is the definition of a team that can lead the capability development effort. The team would typically include a sponsor from the business management, a process owner and a senior SE manager plus a project manager. Support from someone skilled in organizational change is recommended.

Step 2) Defining the Scope for MBSE Capability Gap Analysis

Before analyzing the MBSE capability, it is crucial to define a focused and well-justified scope. This ensures the gap analysis produces actionable insights within available time and resource constraints. The scope should reflect a balance between organizational ambition and the current maturity level. An overly broad assessment risks superficial results, while a narrow scope may miss systemic issues.

The scoping shall consider the balance between Business Needs and Capability Development. For this the contextual factors mentioned previously shall be revisited, i.e. Business, Architectural, Process and Organizational, to assess what is reasonable scope, short-term and long-term for the MBSE Capability development.

Step 3) Perform MBSE Capability Gap Analysis

A capability gap analysis involves a systematic comparison between the current state of MBSE implementation and the desired future state. This analysis provides the foundation for identifying areas of improvement and defining actionable steps toward the MBSE capability development. The process typically involves three core activities:

1. Determining and documenting the current MBSE capability level – capturing existing practices, tools, skills, governance, and outcomes.
2. Defining the desired future capability state – articulating what is needed, why it is needed, and how it aligns with business goals.
3. Identifying the gaps – specifying the differences between the current and desired states and formulating requirements or interventions to close those gaps.

The results of the analysis must be clearly documented and visually communicated to all relevant stakeholders, especially sponsors and decision-makers. Effective visualization helps translate technical findings into organizational impact, demonstrating how each gap affects performance, risk, cost, quality, or time-to-market.

In this step, it is also important to ensure that the scope of the analysis reflects real-world constraints such as available budget, timeline, organizational readiness, and maturity. Ambition must be in balance with feasibility to ensure that proposed actions are both impactful and achievable.

Step 4) Develop Implementation Plan

Based on the gaps, identified capability element actions are defined to close the gaps. Each action can then be laid out in time as how they build on each other. It is important to consider all actions so that a coherent set of actions can be proposed for implementation in an incremental way. Figure 13 hints that in most cases actions to improve governance and organizational capability are of outmost importance and should be a focus in the early phases.

	Phase 1	Phase 2	Phase 3	Phase 4
Governance & Organization				
Process & Process Support				
Information Architecture & Technology and Infrastructure				

Figure 13 - Identified actions for organizational capability elements (Green boxes).

Good practice is to use existing projects to apply selected parts of the organizational MBSE capability vision. This incremental approach provides for demonstrating the value and hence creates buy-in as well as lessons learned that can be tailored into the organizational MBSE capability before implementing the practice in the overall enterprise. This exchange between organizational and project is referred to the Green (organizational) and Blue (project) track approach, see Figure 14.

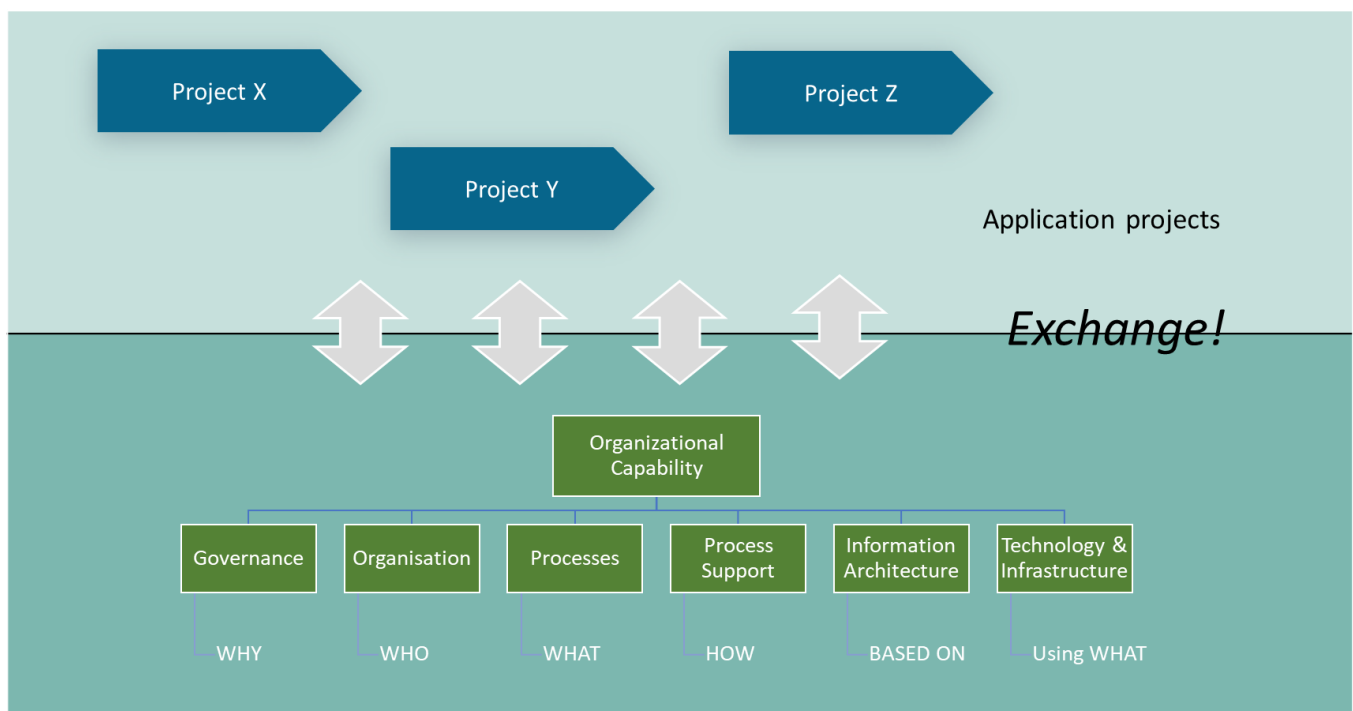


Figure 14 – The blue and green track approach

"Regardless of the magnitude indicated by the capability gap analysis, it is recommended to accommodate for a transition period in the implementation plan. The transition period is preferably kept small (clean cut if possible) and considerations to plausible migrations of legacy data and reverse engineering of legacy systems is given. In the transition planning it is also good to consider impact on other line organizations impacted by MBSE (Verification, Safety, Security, etc.) that might have grown accustomed and dependent on documents and textual requirement. Failing to plan for such impacts will short term reflect poorly on the newly adopted modelling method."

Step 5) Implement and Follow Up

Below are some key factors to successfully implement the MBSE capability elements.

1. **Empower others to act with the vision** - Put in place the structure for change and continually check for barriers. Removing obstacles can empower the people you need to execute your vision, and it can help the change move forward. Meet continuously with management to pick up on problems and obstacles. Typical obstacles have to do with time, resources or lack of knowledge.
2. **Identifying indicators** – Short-term wins depend on having identified good indicators to measure and follow up. Support for how to measure the enterprise operation is provided in [14].
3. **Promote short term wins** - Reward the successes as soon as they occur by emails, intranet, newsletters or key performance index boards or even by throwing a party.
4. **Pay attention to feedback** - Be open to feedback. Take part in existing forums to pick up ideas and viewpoints. Make sure to display the goals/ objectives and continuously show what has been accomplished.

Step 6) Establish the Platform for Message and Communication:

Succeeding in introducing and enhancing MBSE capability is very much about continuously providing message and communication as it involves so many stakeholders. Here are some suggestions:

1. **Establish a vision** - A clear vision can help everyone understand why they are asked to do something. When people see for themselves what is to be achieved, then the directives they are given tend to make more sense. Develop a short summary (one or two sentences) that captures what you "see" as the future of your organization. The vision could explain: Where do we want to go? Why change? What are the consequences if nothing changes?
2. **Translate the vision into terms of “What’s in it for me”** - Tie everything back to the vision. Ask stakeholders: How would you want to change your way of working to start moving towards the vision? Take advantage of keypersons to translate their vision to their area of work. Make sure the leaders (executives, team leaders, project managers, system owners and informal leaders) are on board by informing, engaging communicating how the day-to-day activities will be facilitated and how others will benefit from the efforts.
3. **Communication planning** - Your message will have strong competition from other day-to-day communications within the organization, so you need to communicate it frequently and powerfully, and embed it within everything that you do.
4. **Use clear and consistent language and terminology** - Avoid unnecessary complicated terminology and jargon as much as possible. Try to use standard terms.

This may sound easy but never underestimated the power of “right” information.

The Capability Elements described

The following sections will elaborate on each of the different Capability elements.

Governance

A defined governance for MBSE enables an enterprise to manage its MBSE capability as a discipline based on a set of principles. Clarified responsibility and methodologies guide both in terms of practice for different engineering disciplines and knowledge management for the enterprise as a whole. Governance is an essential element to establish and maintain a wholeness of the MBSE capability elements as defined in the capability model, see Figure 11. Without proper governance even the best organized enterprise with effective processes, right information architecture and efficient tools will not achieve a sustainable MBSE capability. The introduction, sustainment and evolution of the enterprise MBSE capability depends on governance. The means to achieve this include:

1. establishing a MBSE mind set in the enterprise by conveying the purpose, vision and mission of the MBSE capability. This requires management buy-in.
2. a leadership that leads the enterprise in the journey towards its MBSE vision. This requires endurance.
3. a relevant and adequate set of tailored standards and policies. This requires a good insight to both the relevant standards as well as a good understanding of the context (business, organizational and product/service) to which the standards need to be tailored for.

It is preferable that MBSE is acknowledged and sponsored by the enterprise central management group. The MBSE governance does not need to be a dedicated organizational part as such but the technical application of MBSE and its principles needs to be part of the established vocabulary for technical follow up and technical documentation.

A success-factor of governance is to establish a strategy for adoption and roll out of the desired capability built on Systems and Software Engineering - System Life Cycle Processes (ISO/IEC/IEEE 15288). The standard provides a complete set of processes defining *what* is necessary to manage a technical system through its lifecycle. (Note: it does not define *how* these processes are applied, which is a tailoring effort for each organization and project) The processes are divided into 4 categories that can be visualized as illustrated in Figure 15.

If the leadership is not prepared to deal with the challenges that may arise and the leaders lack conviction that MBSE is prosperous, the journey towards MBSE can be jeopardized. Therefore, once MBSE is established, the capability cannot be taken for granted. The influx of new ideas and new senior executives, the organization's turnover at large and a rapidly changing surrounding world means the knowledge management around MBSE-capability needs to be governed.

MBSE capability spans a wide scope and requires an incremental approach as presented in previous sections. The recommended starting point for Governance is to adapt the Technical Processes for a model-based way of working as these are the core processes transforming a need into a solution. To manage the Technical Processes the Agreement and Technology Management Processes are applied. The resources required to execute the overall technical effort are guided by the Organizational Project-Enabling Processes.

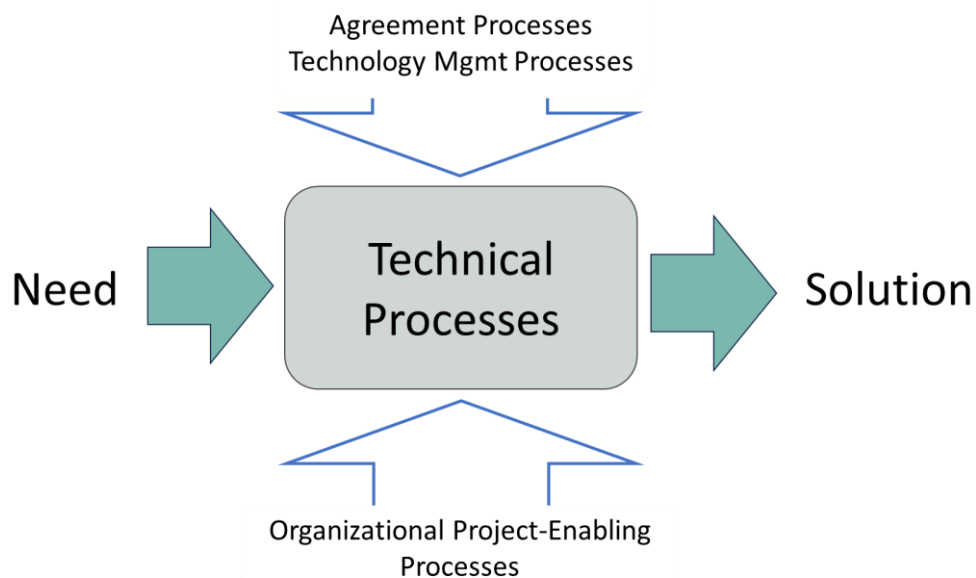


Figure 15. ISO/IEC/IEEE 15288 Process categories in a Governance context

Organization

The purpose of an enterprise's organization is to enable efficient product development, sales and operations by organizing employees, removing responsibility uncertainties and ensuring available and correct competences to the Enterprise.

BAPO-model and Team Topologies [12], dictates that a successful enterprise must align its organization to its business model, architecture and processes, which correlates to the set of context factors to define relevant MBSE capabilities in Figure 11. When dealing with products built up by elements from different engineering disciplines, e.g. mechanical and software, combined it becomes challenging to define and establish an effective organizational structure.

MBSE provides a systematic method to break down complexity and make it possible to visualize different product perspectives including communications structures [15], candidates for modularization and then explore effects for an optimal organizational structure. Hence, by utilizing MBSE to support a reorganization, the enterprise can be more accurate in achieving desired results and produce more value faster.

When changing an enterprise process or methods for systems engineering, like the transition from conventional document-based to MBSE, the organization must also be reviewed and updated accordingly with new structure, competences, roles and responsibilities. The involvement of Systems engineers and their communities is instrumental for this change.

Systems engineering and MBSE are vast subjects that require education and training before engineers can use these ways of working to their advantage. There is a need for both a cohesive education to give the understanding of how MBSE with its different processes, methods and tools are supposed to facilitate the engineering effort, and for short hands-on instruction on how to solve a particular problem at hand.

"Any organisation that designs a system (defined broadly) will produce a design whose structure is a copy of the organisation's communication structure."

Melvin E. Conway

A successful implementation of MBSE in an Enterprise requires at least the following competencies:

- *Systems engineering/architecting* – Definition of purpose of modelling work, what is to be modelled (e.g. extent, quality and granularity) and the roadmap for models according to the Information Architecture. *Associated role: System Architect.*
- *Model architecting* – Definition of the overall structure of the models following the purpose of the modelling work with all its model elements and interfaces and maintains its consistency defined in the System Architecture Definitions. *Associated role: System Model Architect.*
- *Modeling* – Proficiency in defined system modelling language (e.g SysML, UML, Modelica, etc.) and MBSE methods and tools. Implementing of System Models. *Associated roles: Modeler*
- *Model management* – Ensuring the configuration of the model’s versions and variants. *Associated role: (Model) Configuration Manager*
- *Information Mastering* - Ensuring correct and accurate information in System Models. *Associated role: Subject matter expert.*
- *MBSE capability coaching* – Training the organization in adapting and applying the MBSE Capabilities. Writing MBSE training material, performing general training sessions as well as delivering dedicated support to teams upon request. *Associated role: MBSE instructor and coach.*
- *Model Usage* – Interacting with system models to extract relevant information. Reporting needs and improvements of the MBSE System Architecture Definitions. *Associated role: User*

To conclude and underline the importance of a good organization, we would like to share an example of a less successful attempt to change from conventional systems engineering to an MBSE way of working.

“**The company had a mature** system engineering department but involved external consultants to help set up the new MBSE way of working for a development project. When the models were implemented and provided value as intended, the models were handed over to the systems engineering department. However, the organisation had not defined the roles nor appointed Model Architect and Modeler necessary for maintaining the models. When the project was finished and the consultants left, nobody felt responsible or appointed to continue the work and maintaining the models. Over time, the models deteriorated, lost their validity and were eventually scrapped. “

Anonymous Lead MBSE Consultant

In this case, the organization failed to supply the Enterprise with new role descriptions, appoint individuals to fill the need and support the personnel with career paths and education. The story doesn't say, but maybe the reason for the failure from the organization could have been lack of a supporting Governance structure. As a result, the potential of this project-driven initiative to support an enterprise to change towards MBSE never materialized. For MBSE, as in any change in way of working, holistic thinking is needed, including the organization and its effect on the enterprise effectiveness.

Process and Process Support

In any enterprise, processes are vital to order and how to organize the sequence of events which drives the organization and product development forward. Processes are the glue which orchestrates different engineering domains and enable them to work together effectively and to rely on each other's outcome and maintain quality and reduce overtime. Whether your enterprise is guided by project, lean, agile or adaptive methodologies, or maybe a combination of them, well defined and transparent processes are imperative to synchronize and exchange enriched work products from different teams and disciplines. Processes and the events, roles, responsibilities and steps therein, are not static or to be seen as a burdensome control organ enforced by the management. Processes exist to support the developers in their daily struggle and ensure quality and timing in their deliveries. It is therefore important that the employees feel involved and part of the process and that they can influence it for the better - who knows it better than the ones that are affected by it? Processes should therefore be continuously evaluated, and when needed, adapted to the enterprise's current situation and business targets.

MBSE is not a quick fix, nor can it exist in its own silo. It should be regarded as an evolution of existing document-based or document-centric SE process. MBSE needs to be based on working systems engineering processes, e.g. tailored from technical processes and management processes in the standard ISO/IEEE/IEC 15288. The standard and its byproducts, e.g. the INCOSE Systems Engineering Handbook, are helpful guides for system engineers that need to organize their development activities. But do remember that the processes need to be tailored towards *your* enterprise's needs and the individual product development projects.

With a functioning and integrated set of processes in place, you can consider how an MBSE approach can make your product development even more potent. MBSE makes it possible to do things differently but also to do new things that are not possible or feasible without a model-based approach. Some examples of processes and activities that one could do in a new way are design integration, design verification and design validation are provided in [16]. MBSE enables you to do integration, verification and validation in a model to find issues much earlier in the system life cycle, saving time and money. While developing the MBSE capability, one should therefore be open to adjustments of the processes to ensure that processes and methods interplay efficiently.

It can be worth stressing that a model is as important as any other product data, meaning that the configuration management process is an important process to consider. There needs to be a plan for how the model's integrity shall be preserved, which includes its Configuration Items. Other configuration management aspects to consider are how to work in parallel, how to handle variants and how to simultaneously work with different lifecycle perspectives at the same time.

There are, for each process, many opinions on how to execute and manage the process in an efficient manner. A plethora of methods and tools that help execute the processes exist. Which method and tool to

choose depends on your product, organization, legacy, and much more. Every company needs to consider their particular situation and needs to choose tools and methods wisely.

It is common to create guidelines, templates and checklists to aid the developer through the engineering effort. One thing that characterizes MBSE is that more people will use, share and connect to the same engineering information. This has great advantages for cooperation and information exchange, but it also requires the information to be more uniform in how the information is expressed and in how it should be interpreted. Because of this the need for common vocabulary, guidelines, templates, checklists and other helpful aids is even greater when introducing MBSE. It is recommended to early on establish guidelines, templates etc. to avoid rework due to non-compatible representation of engineering data.

Information Architecture

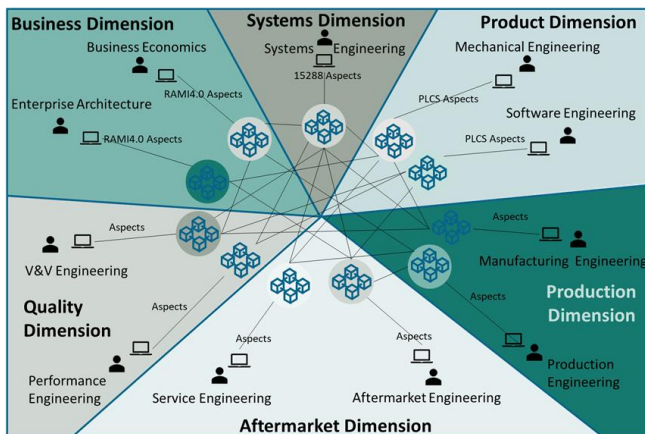
Modern products, even those of modest complexity, are accompanied by substantial data throughout their lifecycle stages—starting from initial studies, moving through design, development, production, and extending to operation and retirement. To effectively utilize modern tools for specification, description, and verification, it is essential to organize this data into structured information items. This structure, while ideally standardized, should also allow for adaptations to meet specific enterprise information needs and conditions. Data is categorized based on the specific needs for information, leading to the development of an information model. The primary goal of this model is to outline which data should be collected and how it should be stored, thus facilitating the mastery of data management as actionable information. Information Architecture in MBSE represents a structured framework designed to organize, store, and manage data effectively through a system's lifecycle. It ensures that data is accessible, understandable, and usable by various stakeholders, thereby facilitating informed decision-making and optimizing system performance. It involves creating standardized information models, connection rules, and interfaces that allow for consistent and interchangeable data, as recommended by standards such as ISO 42010/20/30. This systematic structure provides a standardized framework for structuring and managing business-critical entities within different enterprise models, particularly those related to products. The Information Architecture not only specifies all essential business data and its lifecycle—from creation to retirement—but also outlines its valid interconnections.

In product development, a comprehensive Information Architecture includes defining how system elements are connected to products and how data is linked to these elements. System Elements are conceptualized as manageable functional units with interface controls that promote loosely-coupled development strategies. By establishing an Information Architecture, System Architectural Descriptions can be defined, detailing the necessary information objects and their interrelations representing both static and dynamic aspects. A lack of a well-defined and governed Information Architecture complicates the application of architectural frameworks and descriptions aimed at achieving enterprise objectives throughout the life cycle processes as prescribed by ISO/IEC/IEEE-15288. MBSE is dependent on the clear definition of terms and their conceptual relationships, which are crucial for maintaining traceability of products and services throughout their entire lifecycle across various engineering disciplines.

With MBSE it is now possible to create one aggregated model for the enterprise. This can now be adopted for different stakeholder perspectives like projects and different engineering dimensions to secure that the shared common data is the same for all...

When various organizational tools adopt a common information model, they enhance compatibility and facilitate efficient data exchange across business units, as expected. This is often referred to as the Digital Thread as portrayed in the below Figure 16.

Information flows w/o common Information Model



Information flows with common Information Model

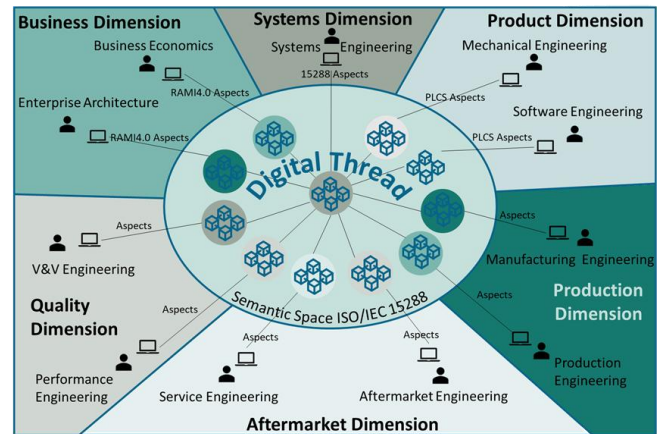


Figure 16. An Information Architecture is at the core of a Digital Thread. Here with an example of with and without a common Information model.

Building an Information Architecture that maintains the integrity of information across enterprise transitions requires significant effort. Initiating this process with business-critical domains and examining their dependencies helps an enterprise effectively address challenges. When implemented correctly, Information Architectures not only supports the realization of business objectives but also facilitates digital transformation by integrating Enterprise and Engineering domains. When different tools use the same information model, they will be compatible and able to handle exchange, and different organizational parts of an enterprise can communicate more efficiently.

When the Information Architecture is documented also the concepts and vocabulary of the enterprise is defined and all the business functions and processes within the enterprise can utilize this common vocabulary.

Conceptual Model Illustration

Consider a conceptual model that connects the Enterprise model (Enterprise perspective) with other plausible engineering aspects (Engineering perspective) within what we term the System Model, see Figure 17. This conceptual model explains how different domains interact and collectively contribute to a unified business enterprise framework to ensure that the gap, mentioned earlier in MBSE Desired state, is to be closed. A frequent challenge for many companies is the absence of traceability from the strategic business objectives defined in the Enterprise Model to the Product Structures in the Realization Structure.

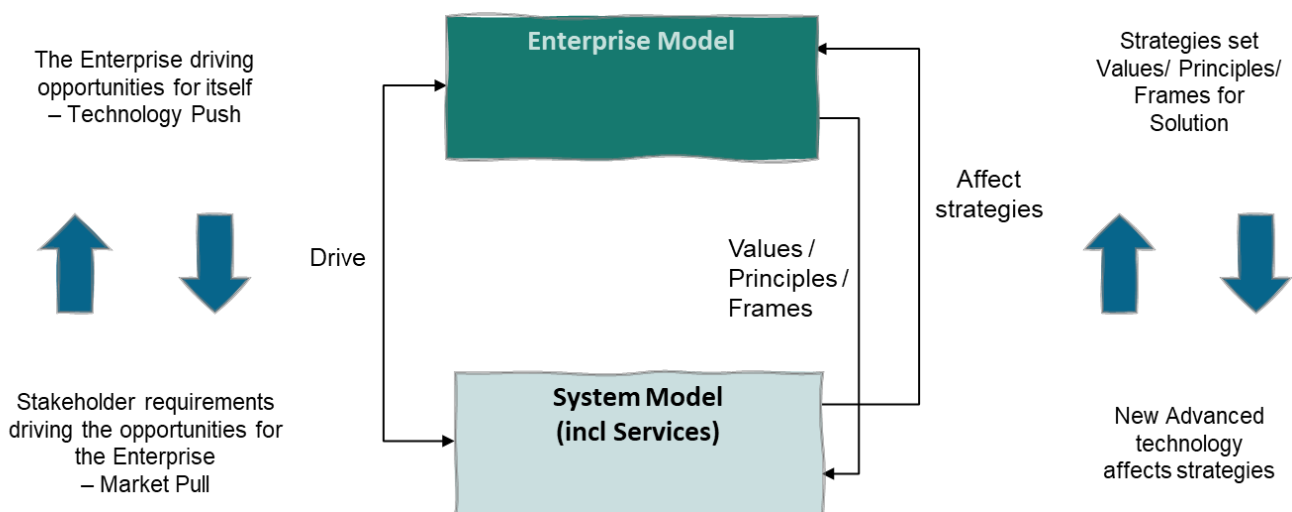


Figure 17 - A conceptual model that connects the Enterprise model with other plausible engineering aspects.

This Reference Model demonstrates a dual "Drive" relationship between the System Model and the Enterprise Model, where market demands and stakeholder requirements generate a Market Pull, and technological advancements create a Technology Push. Strategies from the Enterprise Model establish values and frameworks for the System Model, which are adapted as new technologies emerge. This model not only supports top-down and bottom-up traceability but also ensures alignment between strategic business goals and operational structures, leading to the intended business outcomes. In conclusion, using this reference model as a framework allows enterprises to translate their strategic goals into technical specifications and tangible products effectively, ensuring that the business objectives are met through the MBSE approach. This is further elaborated below.

Walkthrough of reference model; Adding the System model in its Enterprise perspective.

The Enterprise Model with its Mission/Vision and Business Objectives drive Strategies which lead to values and principles for how the business should be driven and in turn conceptually frames a strategic direction for the enterprise defined in the Information Architecture. The Information Architecture drives the System Model, through the Needs, the basis and frames for the System Architecture Definitions. Now the System Architecture Definitions can be instantiated as System Structures, see Figure 18, which in the long run will affect the enterprise strategies.

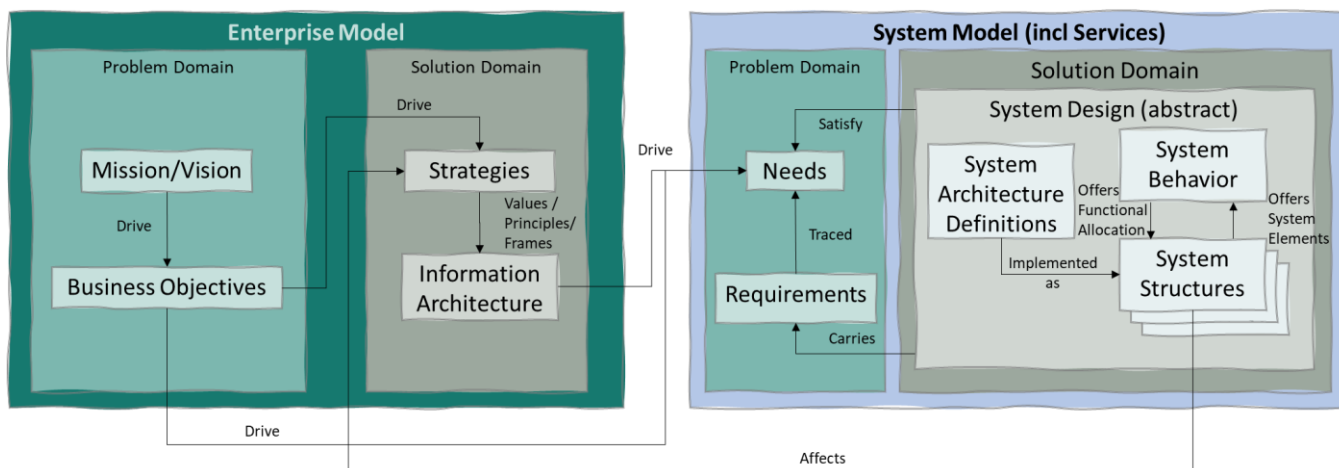


Figure 18 - The close relation between Enterprise and System

The System Structure in the System Design, below in Figure 19, is the first physical image of the System with its internal structure and variants and this abstract System Structure will on a high level “master” the content of the technical detailed Engineering BOM’s in the Product Structure.

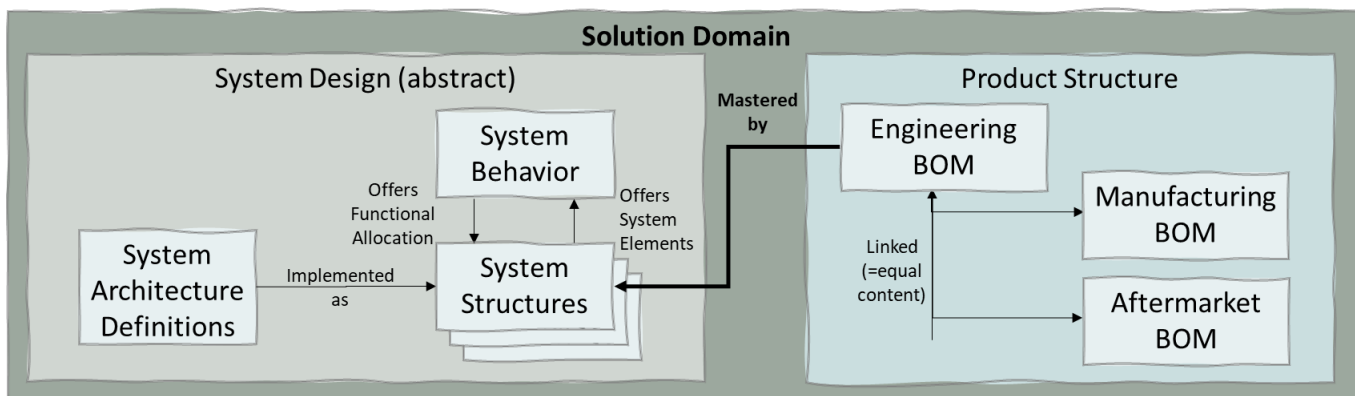


Figure 19. – System Structures mastering the Product Structure.

With this we determine that the Engineering BOM is realized by the System Structure and not the other way around, and now we have the means to ensure the valuable tracing of the strategic business goals/objectives from the Enterprise Model down to the Product structure. The Engineering BOM is also used to create other linked structures or views of the Product Structures e.g. Manufacturing BOM, Aftermarket BOM, etc.

Finally, in Figure 20, within the System Model we have the Quality Assurance Domain which is a reason for doing any of the work described above. The Problem Domain requires the Quality Assurance Domain to ensure the quality of the Solution Domain or as we could see it that the Quality Assurance Domain assures that the satisfying solution has acceptable quality through Verification and Validation of the Solution Domain.

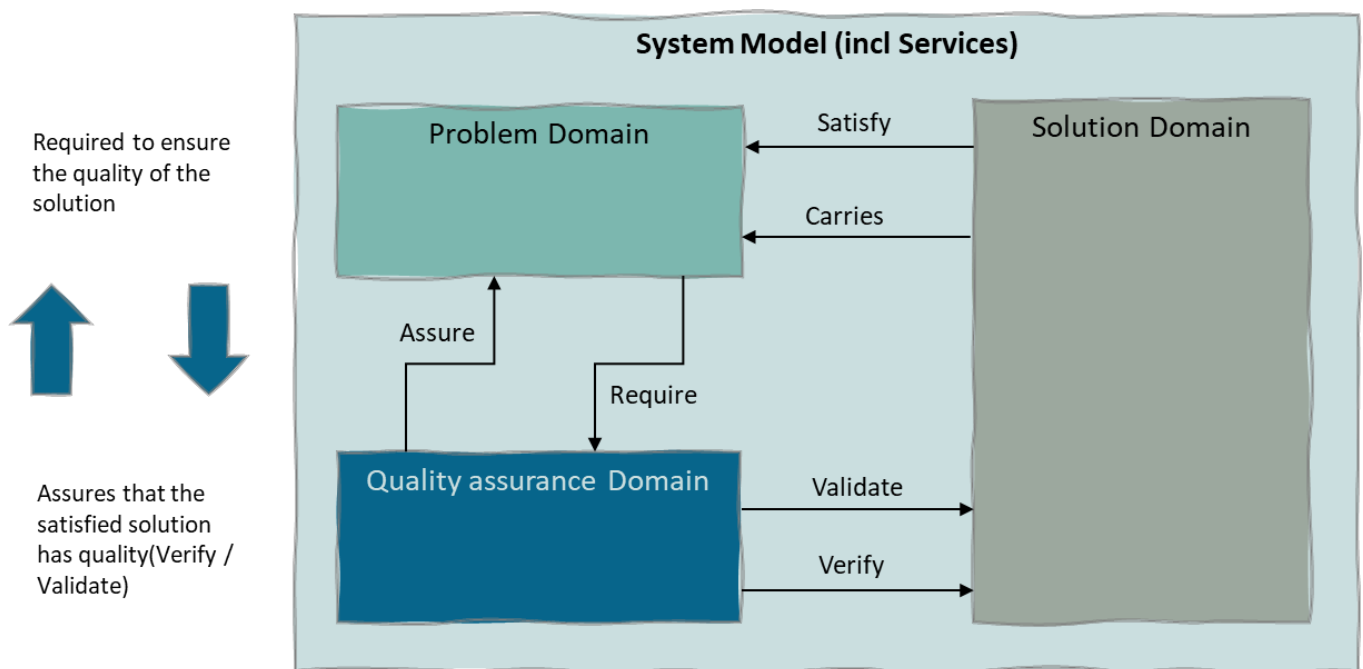


Figure 20 – With focus on Quality assurance domain.

In Figure 21 you will find the more detailed reference model showing that the System Design model will fill the gap between the Enterprise Model and the Product Structure and become the connective tissue as mentioned in “MBSE the Desired State”. The System Design Model can be the “centerpiece” of the Enterprise.

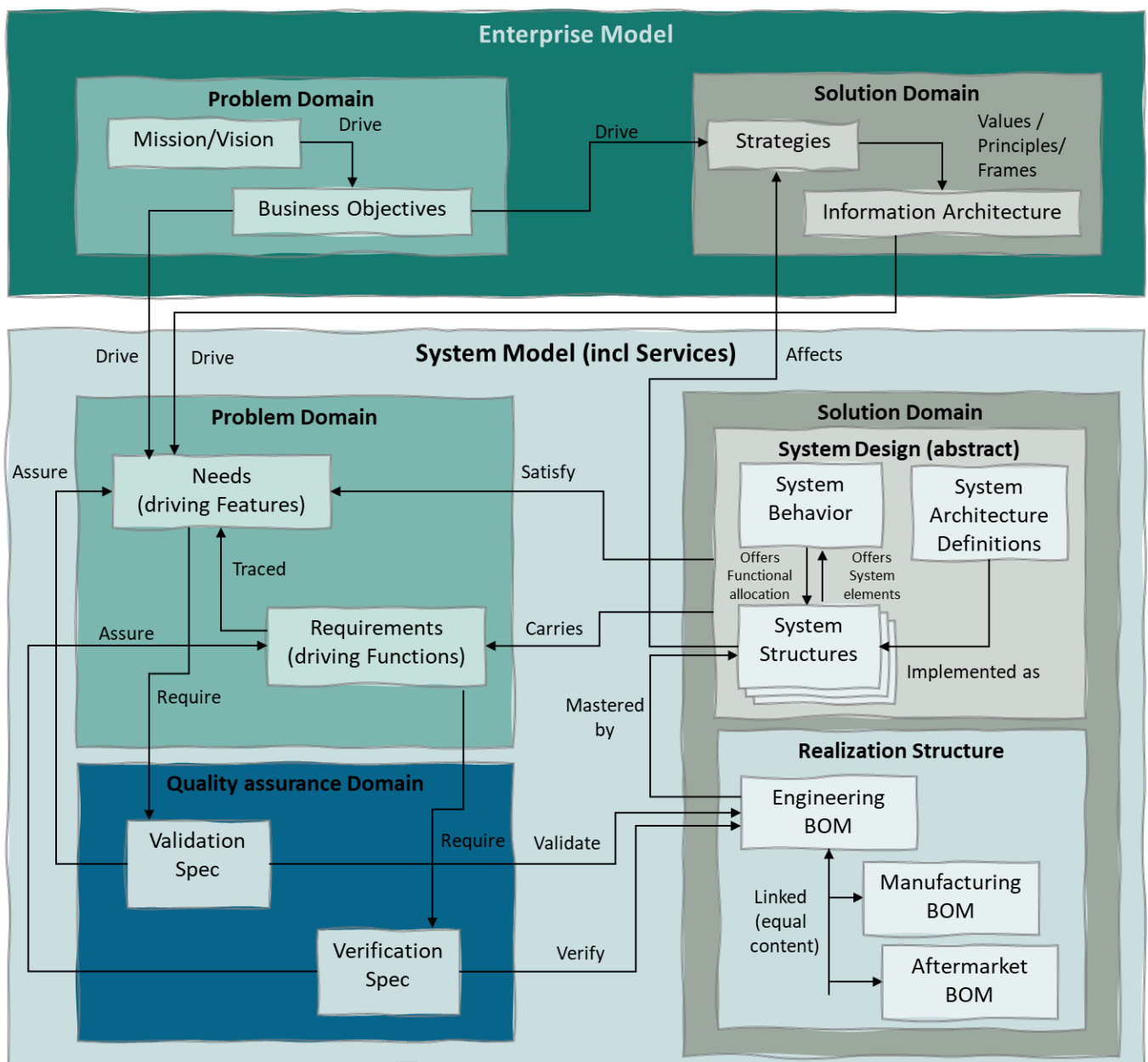


Figure 21. The conceptual System Model in enterprise context. See the image of our reference model as a concept of possible interesting domains, not realized objects. Only a subset of the content per domain is represented.

IT infrastructure

There are endless ways of setting up IT-infrastructure to support MBSE practitioners. By nature, System Engineers are balancing the needs of the many and interacting with most organizational entities. Therefore, it is also likely the information established by System Engineers is strongly coupled to other sources of information.

Before commencing and selecting an IT-solution the landscape of R&D information needs to be hashed out and well understood by the team responsible. It is crucial to understand how your organization's MBSE-practitioners interact with others. It is equally important to understand the enterprise strategic vision when it comes to selecting a suitable enterprise tool suite and infrastructure.

Pro tip!

All things considered, there will never be a perfect match. Settle for less and work with it. Also, never forget explaining why this is the situation to those who think you've made poor choices.

From an IT-infrastructure and database management perspective, the available modelling solutions operate very differently. Ranging from stand-alone solutions, file-based check-in/out solutions (where the entire database is checked in as a file) and all the way to fully integrated solution, where front-end clients operate in the "live" database directly, fully supported of integrated change control. Below three levels of an integrated tool suite is described. These levels depicted in Figure 22 must be matched towards the MBSE capabilities needed for your organization.

Level 1 - File based modelling tools

File based tools allow a model to be treated as a file. You can store the file alongside your documented solution, much like an appendix. Versioning of the model is managed through "check-in" of the entire file. It is up to you whether you treat the file as a part of a larger baseline or if the file contains your functional or developmental baseline internally. Typically, you would only allow for one user at the time to make changes to the model. This setup calls for *external* Configuration management.

Level 2 - Collaborative Database managed tools

A collaborative database allows several users to concurrently work on the same version of a model (but on different parts of the model) potentially as part of a bigger system. The model can contain several instances of an item allowing for changes to be made independently. A single tire model item could, for example, be instantiated four times and independently changed simultaneously. Tools in this category distinguish in-between the 'definition of an item' and the 'instance of the item' to allow for changes to occur separately. Depending on richness, size and connectivity of your model some tools support temporarily diverging parts of the *internal* model by use of internal configuration management of your model. A model can in this case contain incompatible parts (allow for different cadence). The internal CM support in the model is where compatibility and coherence are achieved.

Level 3 - Coherent or “Live” MBSE tools

In a Live modelling approach the model is always coherent. All dependencies of the parts are formally interlinked by associations or by use of definition and instance. Changing an interface at one end automatically changes the interface at the other end. This way the model is always coherent, and no internal or external CM is required.

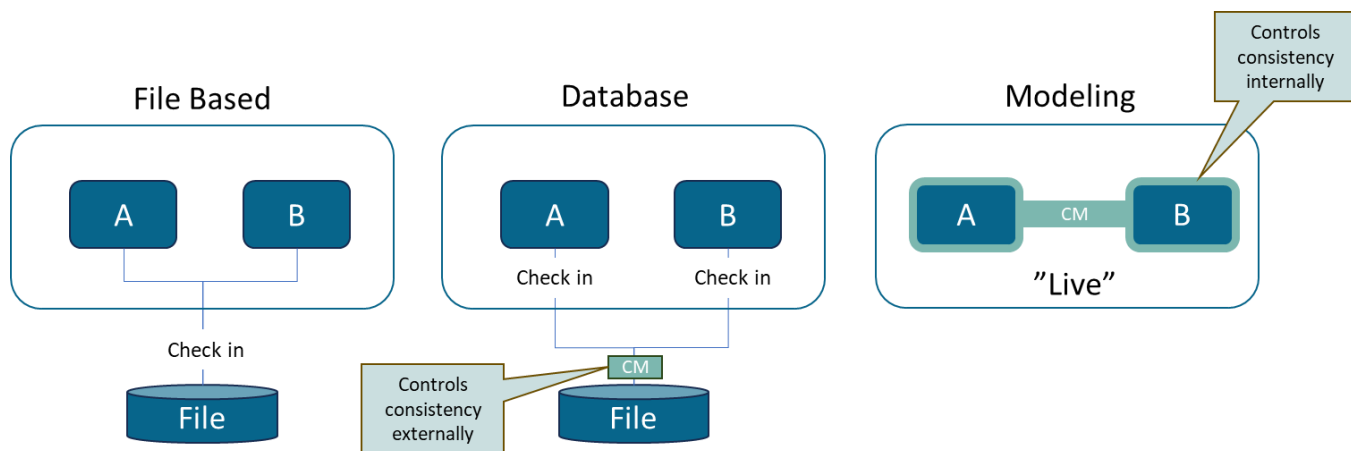


Figure 22. - Coherent or “Live” MBSE tools

For system modelling there are a number of commercial and open-source modelling tools available. Usually, the tool vendors also supply a suggested modelling method that proposes how to use the tool in a good way. To achieve effective model-based work there are three known fundamentals: language, method and tool. Examples of available vendors, tools and methods are listed in Table 1.

Supplier	Tool	Method
IBM	Rhapsody	Harmony
Dassault	Catia Magic/ MagicDraw	MagicGrid
Zuken Vitech	Genesys/CORE	STRATA
Open Source	Capella	Arcadia
PTC	Modeler (Windchill)	CESAM

Table 1 - Examples of available vendors, tools and methods are listed

Part 3 - Conclusions – Reaping the Benefits

In conclusion, enhancing an enterprise's MBSE capability is essential for thriving in today's increasingly complex and fast-paced product development environment. As businesses face rising demands for speed, efficiency, and agility, MBSE offers a systematic approach to managing complexity and driving digital transformation.

A key takeaway is that MBSE should not be seen as a simple implementation of tools but as a holistic capability that integrates various business and engineering functions. The transition to MBSE enables better platforms for communication, faster learning, and improved decision-making through a model-centric approach, where information is consistently shared across stakeholders and disciplines.

This white paper provides a roadmap for establishing a robust MBSE capability by focusing on a comprehensive, balanced strategy that addresses not only tools and technology but also governance, organization (people), processes and support, and information architecture. This is presented in the paper as the MBSE Capability Model where each of the capability elements are elaborated.

One of the central themes of this white paper is the critical linkage between the enterprise domain and the system & service domain. The importance of traceability of products

and services throughout their lifecycle and different engineering dimensions can't be neglected. MBSE ensures traceability from business objectives to technical implementation, bridging the gap between strategic goals and engineering execution. MBSE facilitates this by capturing business needs, transforming them into system requirements in the System model, and ensuring traceability across all levels—from enterprise architecture to product design. This helps validate those technical solutions align with business goals, reducing misalignment and inefficiencies.

At the heart of MBSE is the System Model, which forms the foundation for organizing and managing the information architecture that supports the enterprise's needs. The System Model acts as the authoritative source of truth, providing a single, coherent framework that connects different layers of information, from conceptual business goals to technical system behaviors. This allows for consistency, traceability, and reusability of knowledge across the organization.

There is too much focus on gaining a tool when exploring MBSE. For anyone to succeed in doing a major change, like MBSE, they must understand the importance of building a solid capability supporting that change.

"A fool with a tool is still a fool!"

Grady Booch

The information structure ensures that all elements of the system—requirements, architecture, design, validation, other models and more—are linked and can be accessed in a way that meets the specific needs of different roles, whether they are in management, engineering, or operations. When an Information architecture is documented also the vocabulary of the enterprise is defined and all the business functions and processes within the enterprise can utilize these common definitions contributing to enterprise integration and knowledge base.

By grounding your systems engineering work in a unified system model, rather than relying on isolated information found in documents or scattered digital artifacts, you can fully leverage the advantages of MBSE. Through the adoption of MBSE, enterprises can achieve several key benefits, including:

- **Improved Communication and Collaboration:** MBSE provides a common language and framework for communication between different engineering and business disciplines, improving clarity and reducing misalignment.
- **Enhanced Traceability:** Capturing relationships between system elements enhances traceability throughout the product lifecycle, which is crucial for ensuring alignment between strategic goals and technical execution.
- **Agility and Innovation:** MBSE fosters fast learning and agile development by enabling rapid iteration and early validation of designs through simulations and modeling.
- **Reduction of Rework:** By identifying issues early in the development process, MBSE reduces the need for costly rework and accelerates time to market.
- **Scalability and Future Readiness:** The system model becomes the authoritative source of truth, creating a digital platform that enables scalability and supports emerging technologies like Digital Twins, machine learning, and system-of-systems engineering.

However, the journey to an effective MBSE capability involves more than just adopting new tools; it requires strategic leadership, proper governance, and a cultural shift within the organization. Organizations must invest in education, process development, and infrastructure, ensuring that all stakeholders are aligned and that systems engineers, model architects, and other key roles are well-defined and supported.

The lessons learned from other companies show that achieving success with MBSE depends on establishing a balance between business needs and technical capabilities. It also highlights the importance of strong governance, ongoing training, and a clear vision for how MBSE fits within the broader enterprise strategy. When done right, MBSE provides a powerful framework for handling complexity and turning it into a competitive advantage in the digital age.

In conclusion, enterprises that successfully develop their MBSE capability will find themselves well-positioned to handle the increasing demands of digital transformation, improve product quality, reduce development risks, and ultimately deliver greater value to their customers. The implementation of MBSE is no longer optional but a crucial step in securing an enterprise's future in a highly competitive, complex, and interconnected world.

Lessons learned

The change dilemma

When implementing new processes or new ways of working, it's crucial to consider how this is received by the organization.

In Manufacturing, every part of the organization takes responsibility for supporting a new process to avoid costly production stoppages. Everyone in manufacturing understands the high stakes.

However, in Product Development, the response can be different. Some parts of the organization may resist the new process, thinking, "We've never done like this way before," or "This won't work."

On paper, the new process might seem perfect and now implemented, and management may believe it will enhance their efficiency and reduce vulnerability as intended. But what happens in reality?

Issues often arise later, sometimes much later and if something goes wrong in product development, there are no immediate losses. Of course it will be consequences, delays may occur, or failures in delivering what stakeholders need, or having to redo solutions, but this doesn't have direct immediate consequences. It's just issues that need to be solved, preferably by a taskforce with a group of heroes saving the day.

The problem is that these issues may not be linked back to the new process, especially if years have passed since its implementation.

The conclusion here is the importance of understanding the full picture of the organization, how cause and effect can make a difference. In this case the cause has no effect and therefore issues can occur. To follow up on an implemented process change will make a difference.

Abbreviations

Abbreviation	Description
API	Application Programming Interface
BAPO	Business, Architecture, Process, and Organization
BOM	Bill of Materials
C3	Complete, Consistent and Coherent
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
EBOM	Engineering Bill of Materials
ERP	Enterprise Resource Planning
ESG	Environmental, social, and governance
FDIS	Final Draft International Standard
FEM	Finite Element Method
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
IT	Information Technology
JTC	Joint Technical Committee
MBOM	Manufacturing Bill of Materials
MBPLE	Model-Based Product Line Engineering
MBSE	Model-Based Systems Engineering
MODAF	Ministry of Defence Architecture Framework
OT	Operational Technology
PaaS	Product-as-a-Service
PLE	Product Line Engineering
PLM	Product Lifecycle Management
PSS	Product-Service Systems
R&D	Research and Development
SAFE	Scaled Agile Framework
SE	Systems Engineering
SOA	Service Oriented Architecture
SoS	System-of-Systems
SSE	System Security Engineering
SSIF	Scandinavian Smart Industry Framework
SysML	Systems Modeling Language
TOGAF	The Open Group Architecture Framework
UAF	Unified Architecture Framework
URMSM	Unified Reference Model for Smart Manufacturing
VUCA	Volatile, Uncertain, Complex, and Ambiguous

Definitions

Definitions as defined in this document.

Term	Definition
Additive Manufacturing	A manufacturing process that builds material layer by layer, such as 3D printing.
Agile	An iterative approach to project management and software development that emphasizes flexibility and customer feedback.
Analytics	The collection and analysis of data to draw conclusions and make decisions.
Architecture	The structure of a system's components and their relationships.
Architecture and Product Factors	The structural and product-related factors that impact a system.
Architecture Description	A formal description of a system's structure and its component interactions.
Aspect	A specific perspective or view that represents a certain characteristic of a system.
Brownfield Engineering	Incremental improvements on already existing products or services.
Business Factors	The factors influencing a company's operations, such as market, customers, and finance.
Business Objectives	The goals that guide a company's strategic direction.
Capability	The ability to achieve a specific goal or perform a task.
Capability Element	A part of the complete set necessary to establish a capability, contributing to the overall capability purpose
Capability Model	A model describing an organization's or system's abilities.
Complex system	A system with many interconnected parts exhibiting nonlinear behaviors.
Concept	A general idea or understanding of a phenomenon.
Concurrent Engineering	A product development approach where multiple processes occur simultaneously to reduce time to market.
Configuration Item	A configuration item (CI) is any individual component of a system—including hardware, software, documentation, or a combination of these—that is designated for management within a configuration management (CM) process.
Configuration Management	The process of monitoring and controlling changes in a system during its lifecycle.
Constituent Systems	The subsystems that collectively form a larger system.
Cyber Secure System	A system secured against cyber threats.
Data	Information represented in a structured format.
Detailed Design	A detailed specification of how a system will be implemented.
Digital Engineering	Digital Engineering provides an integrated digital approach that uses authoritative sources of systems data and models as a continuum across disciplines to support lifecycle activities from concept through disposal.
Digital Manufacturing	The use of digital tools to plan, monitor, and optimize manufacturing processes.
Digital Thread	A digital connection enabling information flow throughout a product's lifecycle.
Digital Twin	A virtual representation of a physical system or product that is used to simulate, analyze, and predict its performance throughout its lifecycle.
Digitalization	The adaptation of a system, process, etc. to be operated with the use of computers and the internet.
Dimension	A characteristic or aspect used to describe or measure an object.
Enabling system	A system that complements a system-of-interest during its life cycle stages, but does not necessarily contribute directly to its function during its operation stage
Engineering of Systems	The application of engineering methods to design and develop complex systems.
Engineering Perspective	A focus on using system models to capture and manage technical details related to the design, development, and testing of a product. It emphasizes the creation of detailed engineering models and their interactions.
Enterprise	One or more organizations share a definite mission, goals, and objectives to offer an output such as a product or service.
Enterprise Mission	The company's purpose and the overarching reason for its existence.
Enterprise Model	A model describing an organization's structure, processes, and relationships.
Enterprise Perspective	A view of systems engineering that integrates various engineering models with business models and processes across the entire enterprise. It focuses on aligning system development with strategic business goals.
Enterprise Strategy	The long-term plan to achieve the company's goals.
Enterprise Vision	The company's long-term goals and aspirations for future development.
Feature	A specific characteristic or functionality of a system or product.

Feature Model	A model that describes features and their relationships in a system.
Function	A specific task or activity that a system performs.
Functionality	The features and capabilities a system or product provides.
Governance	The rules, processes, and structures that govern a system or organization.
Greenfield Engineering	The development of new products and services.
High Level Design	An overview design describing the main components and interactions of a system.
Information Architecture	The structure and organization of information within a system or enterprise.
Information Model	A model describing the structure and relationships between information elements.
Interface	A point where two systems or components meet and interact.
IT Infrastructure	The technical and digital resources that support business operations, including networks, databases, and servers.
Kaizen	A Japanese term meaning "continuous improvement," focusing on small, incremental changes to enhance efficiency, productivity, and quality in processes and work environments. It involves everyone in an organization, from executives to frontline workers.
Knowledge Management	Knowledge Management is the systematic process of capturing, organizing, sharing, and effectively using knowledge within an organization.
Lean	A set of management practices to improve efficiency and effectiveness by eliminating waste
Lifecycle	The various phases in a product or system's life, from development to decommissioning.
Low Hanging Fruits	Simple and quickly achievable improvements with a significant impact.
Machine Learning	A branch of AI where systems learn from data without explicit programming.
Manufacturing and Supply Chain Perspective	A view of the system from manufacturing and supply chain aspects.
Market Pull	Demand for new products and solutions based on market needs.
Model	An abstract representation of a system or concept.
Model-Based Systems Engineering	The formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.
Monte Carlo-Simulations	A statistical method to simulate and analyze outcomes based on random variables.
Ontology	A formal description of terms and their relationships within a specific domain.
Organizational Factors	Internal factors that influence an organization's operations, such as structure and culture.
Organization	A group of people working toward shared goals within a structured environment.
Problem	A challenge or issue that requires a solution.
Problem Domain	The larger context or field where the problem is situated, such as the business or engineering domain. It includes all relevant knowledge, rules, and constraints of that area.
Problem Space	The set of all possible problems or challenges that could arise within a given context. It includes all variations, complexities, and dimensions of a particular problem.
Process Support	Supporting systems and tools that facilitate the execution of processes.
Processes	A set of interrelated or interacting activities that transform inputs into outputs
Product	Goods or services offered to the market to meet a need.
Product Baseline	The established starting point for a product, from which future changes are made.
Product Development	Product development is the process of bringing a new product to market.
Product Family	A group of related products with shared features.
Product Line Engineering	An approach to managing product variants and common components across a product line.
Product Platforms	Product Platforms refer to a set of shared assets, including common components, technologies, processes, or design principles, that serve as a foundation for developing a variety of related products.
Product Structure	A Product Structure is a hierarchical framework that defines the relationships and organization of components within a product. It outlines how parts, subassemblies, and materials fit together to form the complete product, enabling traceability, configuration management, and efficient planning throughout the product lifecycle.
Product-as-a-Service	A business model where customers pay for the usage or outcomes of a product rather than owning it, with the provider retaining ownership and responsibility for maintenance and updates.
Product-Service Systems	A Product-Service System (PSS) is an integrated offering of products and services designed to deliver value and outcomes to customers, focusing on fulfilling needs through a combination of tangible products and complementary services.
Quality Assurance Domain	The area within a system or process that focuses on ensuring that products and services meet specified quality standards and performance criteria.
Realization Structure	The structure represents how a system is implemented.
Reductionism	A method of analyzing a complex system by breaking it down into its simplest parts.
Requirement	A specific description of what a system must achieve or perform.
Safety	Protection from hazards or accidents within a system.

Scaled Agile	The application of Agile principles on a large scale across an organization.
Security	Protection of a system from unauthorized access and threats.
Service	A function or task performed to meet specific needs or requirements.
Service and Operations Perspective	A view of the system from service and operational aspects.
Service Oriented Architecture	A software architecture where services are the primary components.
Solution	The answer to a specific problem, often through the implementation of a system.
Solution Domain	The context where solutions are derived or applied often includes specific methods, tools, technologies, or frameworks applicable to solving the problem within the given field.
Solution Intent	Solution Intent is the repository for storing, managing, and communicating the knowledge of a solution's current and intended behavior, encompassing its requirements, designs, and specifications.
Solution Space	The set of all potential solutions, approaches, or strategies that could address the problem. It reflects the flexibility and scope of the solution exploration.
Specifications	Detailed descriptions of a system or product's requirements.
Stakeholder	An individual or organization having a right, share, claim, or interest in a system or in its possession of characteristics that meet their needs and expectations.
Synthesis	The process of combining components to form a coherent system.
System	A set of interconnected components that work together to achieve a specific goal.
System Architecture Definition	A specific definition of a system's structure.
System Design Model	A detailed model that describes the structure, components, and interactions of a system, typically used in engineering and architecture to guide the system's development.
System Design Thinking	A creative and iterative process to solve complex problems by designing systems.
System Engineer	A professional engineer responsible for designing, integrating, and managing complex systems throughout their lifecycle, ensuring that all system components work together as intended.
System Model	An abstract representation of a system describing its structures and behaviors.
System Structure	The hierarchical and logical arrangement of system elements.
System-of-Interest	The system whose life cycle is under consideration.
System-of-Systems	A collection of independent systems that cooperate to achieve a common goal, where each constituent system retains its own lifecycle and purposes.
Systems Architecture	Fundamental concepts or properties of a system in its environment and governing principles for the realization and evolution of this system and its related life cycle processes.
Systems Design	The process of creating and specifying the structure and behavior of a system.
Systems Engineering	An interdisciplinary approach and means to enable the full life cycle of successful products, service and enterprise systems
Systems Thinking	An approach to problem-solving that views systems as a whole rather than focusing solely on individual components. It involves understanding how different parts of a system interact and contribute to the system's overall behavior.
Technology	The application of science and knowledge to create tools and systems.
Technology Push	Innovation-driven development through the introduction of new technology.
Term	A defined word or phrase used in a specific context.
Test Cases	Specific conditions or scenarios are used to test a system's functionality.
Test Results	Documentation of the outcomes from testing, indicating if the system meets requirements.
Tool	A tool or system used to achieve a specific purpose.
Twin	A digital representation of a physical system.
Validation	The process of ensuring a system meets users' needs.
Variability Management	Managing variations and configurations in products or systems.
Variability Modeling	A technique used to represent and manage variations in product features, functions, or configurations. It involves creating models that capture different options and variations to handle diverse requirements and contexts.
Variation Point	A point in the system where choices between different options can be made.
Verification	The process of ensuring a system meets its specifications.
View	A representation of a system from a specific perspective.
Virtual Verification and Validation	Digital simulation to ensure that a system meets requirements and works correctly.
50-50	A structured organizational approach that seeks to balance efforts between two main areas, such as operational efficiency and product innovation.
6Sigma	A methodology aimed at improving process quality by identifying and eliminating defects.

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