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(MB)SE Cross-over Value 2024

Potential cross-over of (MB)SE value from other domains to high-tech

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Contents

Summary

This study proposes the adoption of standardized systems engineering approaches, with methodologies selected based on the complexity of the system being engineered. By classifying systems according to their complexity, we can ensure that the most appropriate engineering practices are deployed, thereby optimizing efficiency, reducing risk, and improving the overall quality of the engineering processes for the Dutch high-tech industry in order to stay competitive on a global scale.

Approach of the study

The top-down and iterative approach taken in the study has three stages:

- The first stage starts reasoning from global drivers, towards industry challenges, and possible opportunities for standardized SE/SA processes. Results of the first stage can be found in this report.
- The second stage, after scoping the opportunity space, will identify organizational capabilities with desired effects to eventually be able to measure the actual outcomes of an intervention. This stage requires more resources from TNO-ESI and might be integrated with our current studies (for example the MBSE and DASE study).
- The final stage is needed to actually validate that the standardized approach does have the intended impact and therefore has to be a research or pilot project with one or more industry partners. In this project, further tailoring of the standardized approach might be needed to satisfy the needs of the partner and ensure successful implementation.

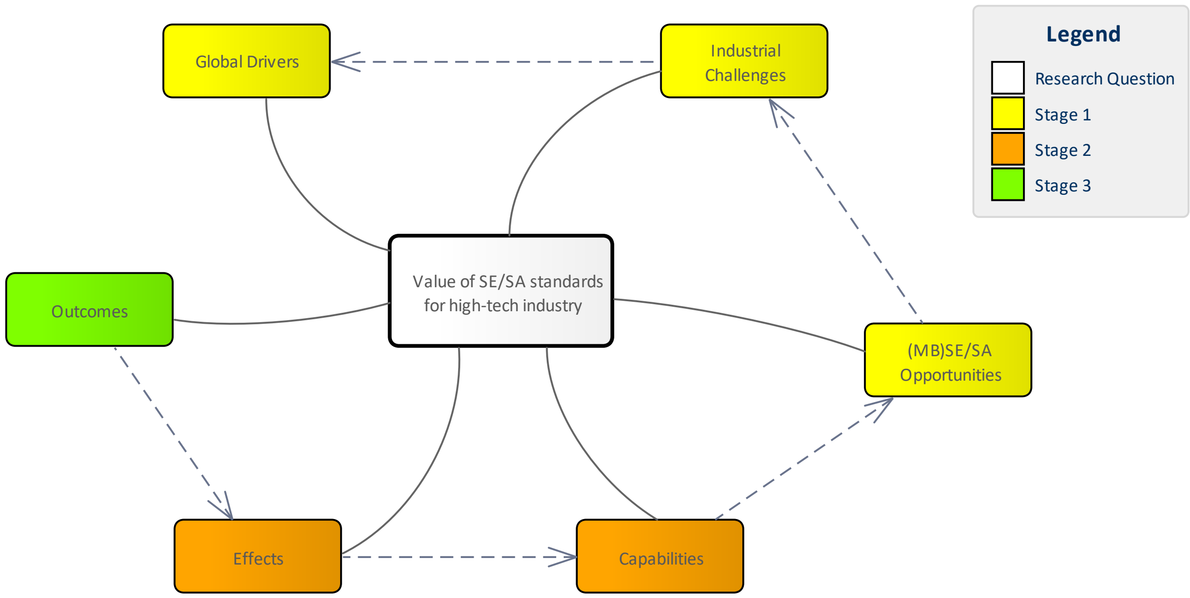


Figure 1: Approach of the study

This mindmap represents the approach of the study. The research question is positioned as a central topic, surrounded by the six main topics. Main topics should be read from top left (drivers) towards bottom left (outcomes) and are related by a dependency. This means for instance if a driver changes, then a challenge might change (and so on towards outcomes). It is a traceable and iterative approach, adaptive to changes during the study period.

Conclusion of stage 1

To conclude the first stage of the study and answer the research question:
'What value can domain-agnostic SE/SA standards that are used in defence, (aero)space, infrastructure and other industries, bring to the high-tech industry?
It provides a reference framework for developing informal, semi-formal and formal approaches for engineering high-tech systems.

Three alternative approaches can be evaluated in terms of effectiveness for the high-tech industry:
1. The informal (or reference) approach
2. A semi-formal (model enhanced/centric) approach,
3. A formal model-based approach.

Since there is no reference approach available for the high-tech domain (every industry partner has its own way of working), this reference needs to be agreed upon in order to perform the trade-off between alternative approaches.

Three industry challenges were identified for applying the alternative approaches to:
1. Loss-Driven Systems Engineering (LSDE)
2. Product Line Engineering (PLE)
3. Requirements Engineering and Management (RE&M)

Digital engineering is considered to be an enabler for dealing with these challenges. Therefore, in Stage 2 clear MBSE capabilities must be defined with expected effects that can actually be measured in Stage 3.

Next steps (stage 2 and 3)

The goal for stage 2 of the study would be to evaluate alternative approaches (informal, semi-formal and formal modeling) to drive Systems Engineering, for different life cycles (development, acquisition, deployment) of high-tech systems with different levels of complexity (simple, complicated and complex).

The approach for stage 2 should be based on learning by doing in a team, in order to get the required competencies, and be able to assess risks & opportunities for each SE approach (based on team experience). Representative reference cases (existing or new) for developing, acquiring or deploying & using a simple, complicated or complex high-tech system should be selected. Stage two should preferably start with a simple case and make the selection together with industry partners in order to stay grounded, motivated and relevant for the high-tech industry.
Important preconditions would be not to reinvent the wheel and:
- Use existing approaches that comply with suggested standards
- Use SysML as notation for both semi-formal and formal modelling
- Use existing tools that implement SysML and formalized extensions (profiles)

Follow up research questions for stage 2:
Why should there be different approaches to SE?
- When to standardize and when to customize a SE approach?
- Which complexity characteristics are key for selecting a SE approach?

When to go for informal, semi-formal or formal modelling to drive SE?
- What is the SE purpose? Concept definition, system definition, system realization and/or system deployment and use?
- What is the MBSE purpose? Business analysis, operational analysis, function analysis, system structure design, system analysis, domain design integration and/or system verification & validation?

How to manage building and supporting models for different purposes (descriptive, analytical, and discipline specific models)?
- When to release a model for a specific purpose (defining model maturity levels)?

Follow up research questions for stage 3:
How to collaborate across multiple organizations?
How to implement (MB)SE within an organization?
- Why MBSE, what are the organizational goals?
- Which capabilities are needed to meet these goals?
- How to plan a strategy or define a roadmap to obtain these capabilities?
- What is constraining each transition towards a new evolutionary stage of the roadmap (people, processes and tools)?

1. Introduction

In the high-tech industry, the complexity of the systems being developed varies significantly. From simple, well-defined subsystems to highly complex systems and even adaptive systems of systems, the engineering approaches required can differ drastically. The overall goal of the study envisions a framework for selecting standardized systems engineering methodologies that are best suited to the specific complexity level of the system of interest. This part focuses on the first stage, where domain specific drivers, challenges and opportunities are identified.

Considering the state of practice, many established organizations have evolved over time and developed their own valuable way of working. Sometimes current development methods are reaching the limits of complexity that can be handled (for example by a single person), and adoption of new approaches is needed to advance the state of practice (for example move towards teamwork including more domain specialists). However, highly skilled people using rather simple methods also constrain interventions towards new approaches using more advanced and specialized development techniques. Often, this means very specific evolutionary changes are needed, in order to stay successful and fit for the future. Small incremental steps must to be carefully planned and managed to enable the transition within an organization or enterprise.

Other domains than high-tech also have encountered the effects of scaling and specializing. As a consequence, Systems Engineering is adopted to educate and train the 'workforce of the future'. Best practices from these domains [14] have been (and are continuously) consolidated towards standards and guidelines [13] for Systems Engineering, which might bring value to the high-tech industry as well. This study aims to look at the specific challenges for the high-tech industry and common opportunities the 'state of the art' of Systems Engineering might offer.

What makes a system complex?

Systems can be classified as simple, complicated and complex systems [1]. The fact that a System, as well as a Project developing, deploying or modifying such a System, has a lifecycle and undergoes changes during its life, causes a large part of the complexity. Often, there is a 'handover' where information is incomplete or missing or where knowledge lacks, gets lost or is misunderstood. So, it is not only technological, but also organizational and social complexity that needs mastering.

It is important to understand that a System sometimes is considered as a Product (realized by a Project) and sometimes as a Service (realized by a Process). This fully depends on the perspective or 'eye of the beholder'. After all different stakeholders have different interests in a System, depending on their perspective or context. Agreement on the problem is essential in understanding the needs for a Product or Service.

Quote: As a system’s diversity, connectivity, interactivity, or adaptivity increases, the risk associated with using simpler methods and simplifying assumptions also increases, and more advanced techniques may be needed. Tools and techniques apply differently to systems on a spectrum of increasing complexity. At the less complex end, the waterfall model for top-down sequential design applies well. At the more complex end, tools such as agent-based models for model-based systems engineering can be used to understand and address complex, dynamic system design challenges. Techniques at the lower end of the spectrum tend to be easier to learn, and simpler and faster to apply, because they make simplifying assumptions that ignore some of the complexity. The practitioner must apply judgement to utilize a mixture of tools along this spectrum that satisfies Einstein’s razor: make things as simple as possible, but not simpler. [1]

When to standardize or customize a process?

The decision to standardize or customize a systems engineering (or architecting) process should be guided by a thorough understanding of business goals and stakeholder needs. When considering the (Dutch) high-tech industry as an ecosystem or enterprise, there might be benefits in standardizing the way of working in the sector.

Standardization of engineering processes may not only be needed for regulatory compliance, but can also have benefits in terms of training and knowledge transfer, quality assurance, efficiency and cost savings due to consistency across projects. However, customization brings along other benefits, for instance when reusability of artifacts consumed and produced (inputs and outputs) of the lifecycle processes of a system is low.

As a follow up of the Helix study [9], the NXTGEN DASE study has started, to identify what makes the Dutch Approach to Systems Engineering specific and how to align education programs of academic partners with continuous learning programs of industry partners. Results from both studies are used to better understand the Dutch high-tech industry and their needs.

Purpose of this document

This version of the document reports on Stage 1 of the study. It focuses on generic drivers and challenges for the high-tech industry (Chapter 3) and suggests some opportunities for (MB)SE/SA to continue with in Stage 2 and 3 of the study (Chapter 4). No specifics for TNO-ESI's industry partners are included in the report. Chapter 5 summarizes the (preliminary) findings, conclusions and recommendations related to the problem defined in Chapter 2.

2. Problem definition

Hypothesis

This study investigates the applicability and value of systems engineering (SE) standards and practices from other domains to the high-tech equipment engineering sector. The study is based on the premise that systems engineering across different domains exhibit similar patterns in terms of architecting and design.

For example: In many domains, stakeholder acceptance goes beyond accepting the basic functionality for operational use. Often there are qualities required from a system. For instance, in railway, automotive and medical domains, all systems require some kind of safety acceptance in order to be allowed to be put into use. Next to this safety quality, there might even be more 'loss-driven' qualities (e.g. reliability, security and sustainability) driving design. It is not uncommon that these qualities are conflicting with the intended use and require balanced trade-offs. Architecting and design methods for these qualities, can be generic.

In defining an approach to perform (MB)SE activities, it is interesting to see where differences and commonalities lie and whether processes, methods and tools from a specific domain can be reused for another or whether specific extensions are needed. Reinventing the wheel might bring additional value, but building on existing knowledge has proven to be more successful. It is common knowledge that the SE standards provide guidelines that need tailoring to fit the needs of organizations and their enterprises [14].

The value of standards

Systems Engineering (architecting included) is a 'discipline under development', where a lot of best practices from different domains are captured by international standards. Recently, some new standards were released on a Unified Architecture Framework (UAF) and (Model Based) Systems Engineering processes, methods and tools. These standards are complemented with a guide for using the UAF and an updated Systems Engineering handbook from INCOSE [13]. The following diagram gives a 'state of the art' overview of these standards and how they relate to each other.

Note: 'domain-agnostic' standards for SE/SA need to be tailored in order to be used in a purposeful manner. It should always be clear 'why' a certain standardized framework, process, method or tool is adopted. The value it adds to the existing way of working should always be clear.

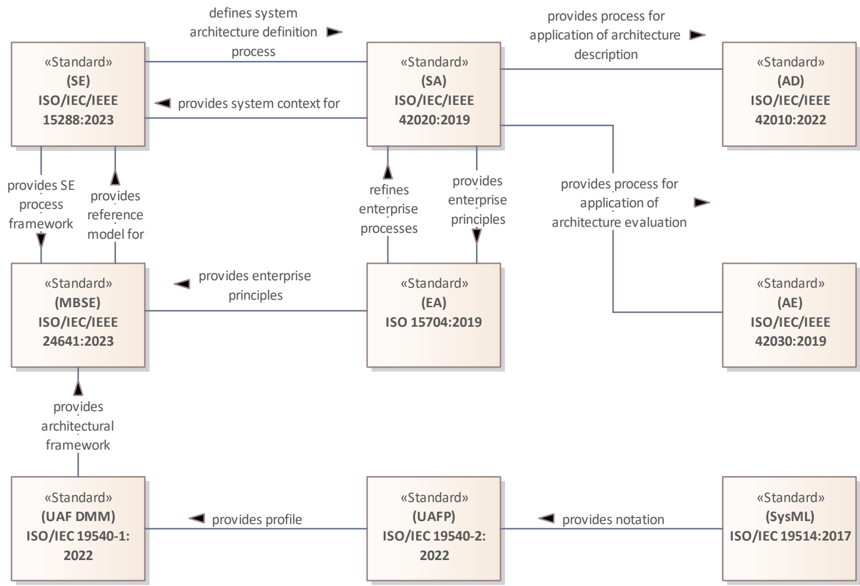


Figure 2: Systems Engineering and Architecting standards and their relations

Figure 2 gives an overview of Systems Engineering and (Enterprise) Architecting standards, which are in fact complementary to each other:

- ISO15288 provides a process framework for the life cycle processes of engineered systems, which also includes system architecting.
- ISO42020 and ISO15704 refines the architecting processes considering not only engineered systems, but other architecture entities as well (enterprise, business, organization, solution, project, etc.).
- ISO24641 provides a reference model for engineering systems by using models supporting: business analysis, operational analysis, function analysis, system structure design, system analysis, domain design integration and verification & validation. Depending on where you are in the lifecycle of a system and what you are trying to achieve, you can make use of this reference model to structure your activities.
- ISO19540 (UAF standards) formalizes the semi-formal SysML notation and provides an architectural framework that can be used as part of a model-based (enterprise) architecting approach.

In general, standards support agreements on interfaces or protocols for businesses, consumers and governments. However, the standards shown in Figure 3 are also used for educational and certification purposes, in order to make sure that Systems Engineers and Architects worldwide speak a common language. This makes these standards relevant for tool vendors to invest in as well. Most commercial CASE tools not only support standardized notations like SysML, but also standardized frameworks like UAF.

The main takeaway is that the use of standards might be an effective solution for sharing knowledge and solving communication problems, especially when stakeholders need to collaborate and require or provide each other's services. This can be a customer versus supplier interaction, but also intra- or inter-organizational interactions (for example between a developer and a manufacturer). In the high-tech industry, it is a common practice to agree on domain- or organization-specific ways of working and a choice whether or not to comply with Systems Engineering and Architecting standards. In other words, there is a balance between what to standardize and what to customize for Systems Engineers and Architects in the high-tech industry.

To give some examples:

1. In concept definition stage, models can be used for business analysis to identify opportunities for a business case or operational analysis to describe the (modified) use cases of a system. In other domains, it is good practice to align on business goals, organizational and system capabilities and their intended effects, as well as translating these needs into stakeholder requirements. Artefacts like concepts of operations (ConOps) and operational concept descriptions (OpsCon) have proven to be very useful for understanding the purpose of an enterprise or change in an organization or system.
2. In system definition stage, models can be used for a (black box) functional analysis and (white box) system design and analysis, as well as specifying the system requirements for different domains designs. Artefacts like 'system level' architecture descriptions, designs and specifications have proved to be very useful in conveying structure, behavior and design constraints for different engineering disciplines (electrical, mechanical, software, etc.). Especially when organizations and projects grow globally and in complexity, domains get more specialized, many disciplines are involved in engineering the system, and multi-layered communication is needed.
3. Models created in the early lifecycle stages can be reused across subsequent lifecycle stages for tracing system requirements towards stakeholder requirements, performing impact analysis on changes and supporting verification & validation purposes. These models can even be used for building a digital twin, representing multiple configurations and implementations of a system in the field.

Research questions

What value can domain-agnostic SE/SA standards that are used in defense, (aero)space, infrastructure and other industries, bring to the high-tech industry?

As input for this study, insights from the following projects and their research questions are considered:

- Helix [9] - What does it mean for an individual or organization to be effective at systems engineering?
- NXTGEN DASE - What is the Dutch approach to systems engineering?
- ArchSkills [16] - What are the required systems architecting competencies in the near future?
- Canvas - How to architect for sustainability and circularity?
- INTERSCT [10] - How can safety and security of a cyber-physical system in an expanding system of systems landscape be ensured?

3. Industry drivers & challenges

This chapter focuses on generic drivers and challenges for the high-tech manufacturing industry.

In the manufacturing industry, there are two main approaches: original equipment manufacturing and original design manufacturing. Key difference lies in ownership and control of product design. An Original Equipment Manufacturer (OEM) produces the product based on specifications provided, and the buyer designs the product. An Original Design Manufacturer (ODM) designs and develops the product, and the buyer can customize it to meet specific needs. Supplier roles of an organization can be classified as: Machine Supplier, Solutions Provider, Maintenance Partner, Performance Partner and Value Partner [5].

The business strategy of a supplier depends on where it is now, and eventually wants to be in the value chain of a business. This strategy should drive the product portfolio by identifying key qualities and differentiators from other suppliers. One of the trends in the high-tech industry is the desire (by the supplier) or demand (by the customer) for 'climbing the value chain' [2, 3, 4, 6]. In other words, changing from OEM towards ODM and/or provider of value added services.

Architecting is used to describe fundamental concepts of a product (or product line) and guide design, realization and evolution of these concepts. A reference architecture might be used to guide product architecting, by connecting the business strategy, and intended market, ensuring that stakeholder needs of both customer and supplier are satisfied [12].

Figure 3 shows a subset of stakeholder roles, organizations that may realize these roles, and actual organizations typed by these organizations.

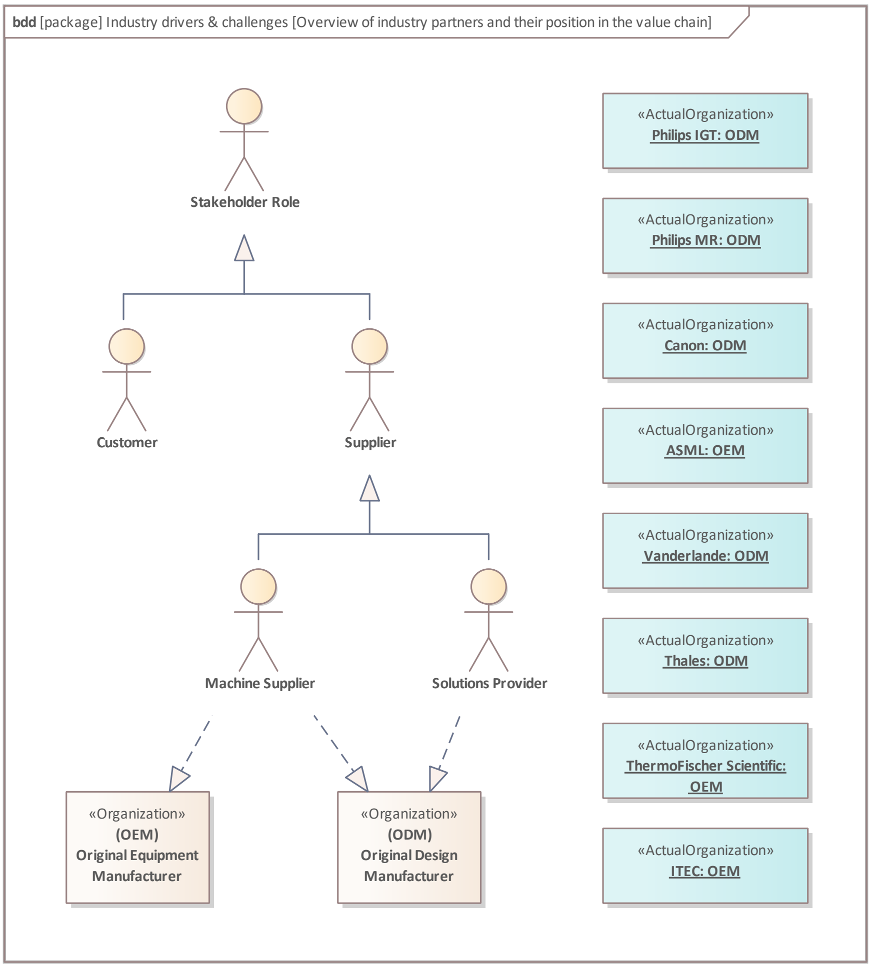


Figure 3: Overview of industry partners and their position in the value chain

The high-tech industry partners of TNO-ESI can basically be classified as OEM's or ODM's. Most of them even provide value added services for operation and maintenance, and might even be responsible for performance during the operational lifetime of the product. TNO-ESI as a knowledge partner of its industry partners, also provides value added services, for example in analyzing operational performance data of (legacy) products in the field or improving the development of new products by providing validated methodologies.

Depending on the business actual organizations are in and roles they play (can be more than one), a specific strategy is needed to stay on top of their game. Basic examples of such strategies are: technical leadership (go for best product), customer intimacy (go for best relation) or operational excellence (go for best operational process or service). Being good at all three is hardly possible.

Some examples: Machine Suppliers might try to reduce manufacturing costs by modularity and agreements with tier suppliers (go for a platform approach). Solution Providers might try to sell their products to new customers and extend the range of services that can be supported by their machines. Suppliers that also have a stake in operation & maintenance of the product, will look into more effective operational scenarios and improved performance (for example: change from corrective or preventive to predictive maintenance strategy).

High-tech industry drivers

In a way, the Dutch high-tech industry can be seen a system of systems or ecosystem, that also faces environmental, social and economic challenges. In order to make sure the enterprise stays sustainable, a change of strategy might be needed as well.

Most high-tech manufactures start as a technical leadership company in combination with customer intimacy and then at some point may have to make a transition towards operational excellence to stay ahead of competition when markets are getting more mature and margins are reducing. Generic (global) drivers would be the scarcity of resources, consisting of both people and materials; the environmental impact human made (engineered) systems have on the environment; and the international competition for acquiring these scarce resources and supplying competitive solutions.

Drivers for each specific organization within the enterprise differ and depend on the type of business and products and/or services provided and required within this business. To elaborate a bit on high-tech products and services, the analogy is drawn with the seven samurai of systems engineering [8].

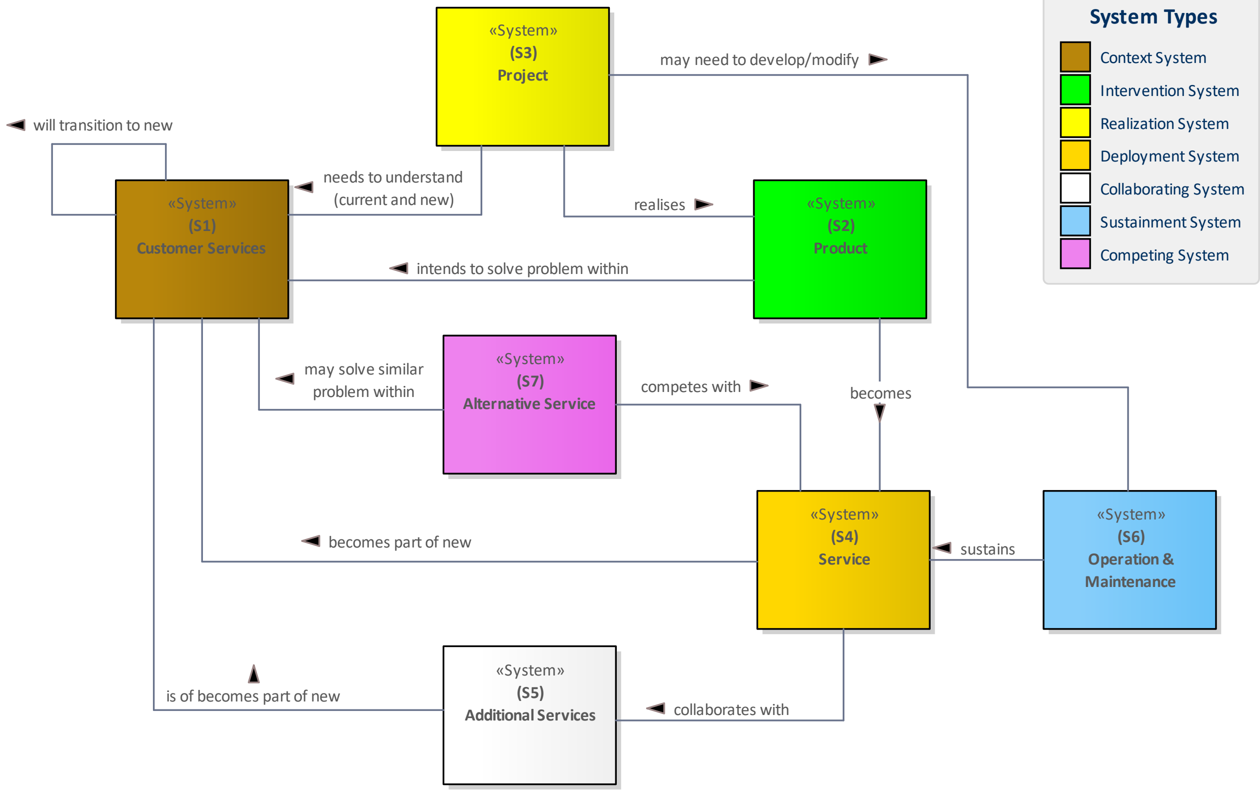


Figure 4: The Seven Samurai

In the high-tech industry:

- The 'intervention system' is considered to be the product (technical machine) that needs to provide a service within a specific 'context system' of the customer. There is an ever increasing need to interoperate with additional services in order to enhance customer services. This is the driving force behind product complexity and causes technological and scientific challenges (do more with limited technical resources).
- Every business has its own 'realization system' or project for creating products and value added services. The increase in product complexity and scarcity of people staffing the project are driving forces behind new ways of working. Changing an organization without losing the value of existing knowledge brings along methodological challenges (do more with limited people).
- The 'sustainment system' consisting of (modified) operation and maintenance requires attention due to a continuous growth in (constrained) value added services. Legacy products together with an increase in demand for reducing the negative impact products and services have on the environment are driving methodological and technological (digital) innovations.
- The 'competing system' being an alternative service provided by a competing organization acts as an economic driver and competes for the same scarce resources (people and materials). Employees are increasingly drawn to supporting higher-level goals than focusing on economic benefits only. For organizations to become future proof; maintaining knowledge assets and cultural values are becoming more and more important [7, 9].

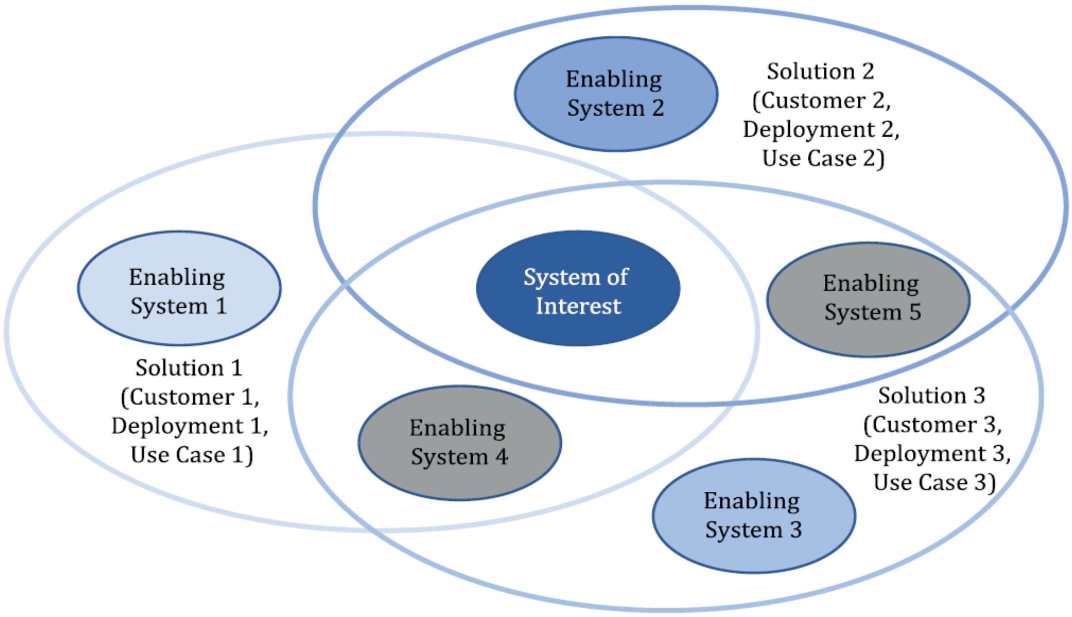
Challenges for original equipment manufacturers

Simply put, machine suppliers naturally want to go for the best product. However, what does 'best' mean? What makes their product unique or better than others? This fully depends on how the product is used (or in other words which service or value it provides). It could very well be that the product is a part of an even larger product, and therefore in need of an integration service. It might even be used in a variety of other products, which then requires interoperability. The opportunity standards offer is a no-brainer considering this challenge.

Integrating third party equipment is not only about technical interfaces (data exchange) but also about interoperability and communication between different stakeholders in the supply chain (information exchange). When complexity in terms of numbers and variants of modules, components and parts increases, so does the amount of information/data exchange. For this reason, most organizations in the high-tech industry are 'vertically integrated' and work in close collaboration. The tight coupling between elements of a product, have resulted in choosing close collaboration and strategic partnerships across the supply chain over a more formal and contractual approach based upon (standardized) interface specifications. This approach was recognized in the DASE project.

Challenges for original design manufacturers

In general, solution providers will go for customer intimacy to make sure there is a smooth transition towards newly provided services. This requires a sound knowledge about the operational processes and realistic scenario's. The value the solution provider brings is more in this knowledge rather than the manufacturing of products. There even may be a shift at play, where commodities are provided by tier suppliers (even directly to the customer, e.g. to save on total costs of ownership). Acquiring products via solution providers will not always be best for the project. Hence, in large complex infrastructure projects the customer will have a contracting strategy (D&B, DBFM or even DBFMO) and the supplier needs to have a supply/acquire strategy for making or buying the product or its components.



System solution contexts [ISO 15704]

Figure 5: Managing the variability challenge

When in control of designing a product (system of interest), you can decide to either standardize or customize (commercialize) internal interfaces. However, there will always be external interfaces towards enabling systems you are not in control of. Solution providers and their customers might benefit from standards, but also here a trade-off is needed at system of systems level.

As long as every specific solution has its own specific designer, there will never be standardized interfaces between constituent systems that make up a system of systems. The only way to solve this dilemma is by (international) collaboration between customers, suppliers and standard developers, focusing on common (enterprise) goals for standardization. There have been many initiatives on this in other domains (telecom, railways, automotive, process industry) from which high-tech industry can learn.

Challenges for value added services

A value-added reseller is a firm that enhances the value of third-party products by adding customized products or services for resale to end-users. Value-added resellers play a prominent role in the information technology (IT) industry, providing additional hardware, installation services, consulting, troubleshooting, or other related products or services on top of core products. Value can be added across the whole lifecycle of a System of Interest: during concept definition, system definition, system realization, operation & maintenance and system retirement.

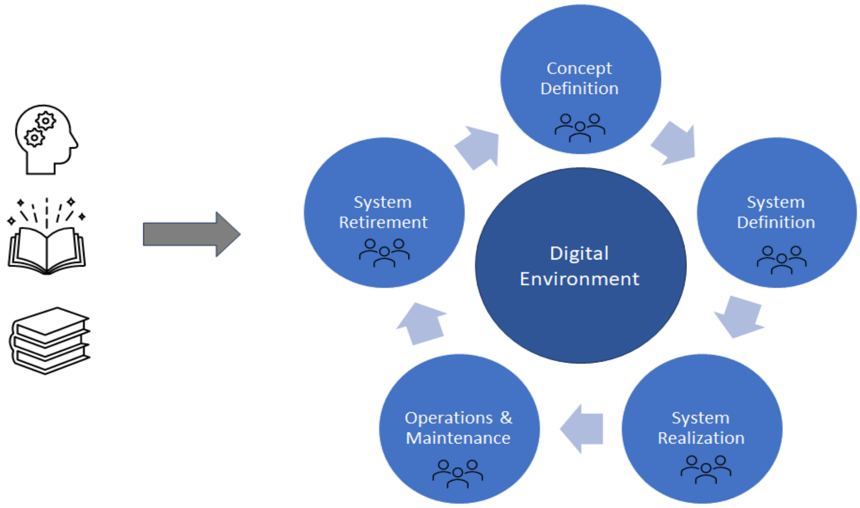


Figure 6: Managing the digitalization challenge

Due to increased complexity of high-tech products and services, traditional SE-approaches have reached the limits of what systems engineers (individually) can handle. Collaboration between architects, designers and domain experts nowadays already rely heavily on domain-specific models. Making the transformation as an organization towards model-based systems engineering is an even bigger challenge. For this 'openness to change', other competencies are needed than the traditional ones. Future practitioners of digital engineering approaches should prepare for a steep learning curve.

A 'digital twin' is often seen as the holy grail, but before you have a virtual representation of the realized system, you need to define your concepts and systems. These activities also result in models that need ownership. A digital engineering environment supports all modeling activities, where designers, builders, users, operators and business owners can collaborate and share their models, views and viewpoints. Standards provide methods for model-based systems engineering, that can help scope the right problem and solution space regarding the support of SE by modeling. There is commercial tooling available supporting such digital environments and standardized notations & methods.

Note: When developing a complex **system of systems***, where multiple organizations are involved and many stakeholders might have an interest in the system (owner, user, operator, maintainer, integrator, builder, designer, ...), loss-driven qualities are the driver for system acceptance. For safety and security, independent assessors take part in this acceptance process, but taking sustainability into account is rather new. Standardized (MB)SE approaches might offer opportunities for balancing a system of systems, by making sure that loss-driven qualities are properly accounted for across the constituent systems that together make up this system of systems.*

4. Opportunities for (MB)SE/SA

Considering the drivers for high-tech manufacturing, and challenges for OEM's, ODM's and value added service providers, multiple business goals and objectives per organization or ecosystem can be defined. Opportunities for (MB)SE/SA emerge especially when ownership of products, services and values change within the ecosystem, and organizations need to communicate and collaborate to manage these changes.

Preliminary results/insights

Suggest to look for opportunities related to:
1. Developing a system of systems with clear enterprise goals for loss-driven quality (acceptance of SoS by multiple stakeholders f.i. by independent assessor)
2. Decision support for product portfolio management (alternative trade-off analysis and variant selection/reduction)
3. Acquisition/supply chain support (sharing information, data and models via a digital environment)

Proposed Framework:
1. *Complexity Assessment: Develop a complexity assessment tool to evaluate the system's complexity based on various parameters, such as size, interconnectivity, dynamic behavior, and technological novelty.*
2. *Categorization of Systems: Define categories for systems based on complexity (e.g., simple, moderate, complex, highly complex).*
3. *Standardized Methodologies: For each category, identify and standardize a set of systems engineering methodologies that are most effective. This includes processes, tools, and techniques tailored to the complexity level.*
4. *Implementation Guidelines: Provide detailed guidelines for the implementation of these standardized methodologies, including best practices, case studies, and potential pitfalls.*

Benefits:
- *Efficiency: Streamlined processes tailored to system complexity can reduce development time and resource expenditure.*
- *Risk Reduction: Appropriate methodologies can help identify and mitigate risks early in the development process.*
- *Quality Improvement: Standardized approaches ensure consistent application of best practices, leading to higher quality outcomes.*
- *Scalability: The framework allows for scalable engineering practices that can be adjusted as the complexity of the system evolves.*

Different approaches to Systems Engineering

As Systems Engineering is considered to be an enabler for successful realization, use and retirement of engineered systems, depending on its purpose a level of formality can be selected.

Suggest to introduce three generic SE approaches for the high-tech industry:
1. The informal approach to high-tech systems engineering (document based)
2. The semi-formal approach to high-tech systems engineering (model enhanced/centric)
3. The formal approach to high-tech systems engineering (model based)

Implementation strategies for MBSE

As Model Based Systems Engineering is considered to be the formalized application of modelling to support Systems Engineering, different implementation strategies can be selected.

Suggest scenario's for:
1. Transition from informal to semi-formal SE approach
2. Transition from semi-formal to formal SE approach
3. Transition from formal to semi-/informal SE approach (optional)

5. Study results

This chapter summarizes the findings, preliminary conclusions, and recommendations for future initiatives towards digital engineering for managing a supply chain, product portfolio, services or stakeholder values.

Findings

Insights and observations based on the considered projects:

- So far, no 'Dutch' approach to engineering high-tech systems has been identified in the DASE project. Only company specific ways of working for the development of low volume, high capital, and high precision machines. Every company has its own culture, and often practices a pragmatic and human-centric approach, rather than a systematic one.
- Enterprise architecture and systems engineering processes, as defined in the ISO standards, are not recognized as such in the high-tech industry. So far, the DASE and ArchSkills projects have focused on individual SE roles and competencies rather than team roles and organizational capabilities. This is reflected in the way responsibilities are assigned to individual roles in flat organizations (the people-oriented approach). The downside of this approach is that a lot is expected of people in terms of competency profiles (a need for more unicorns).
- Of all 7 samurai, most of the focus goes to the product. There is no clear ownership within the organization for the other 6 systems. The MBSE study [15] shows that some companies have already started initiatives regarding a transition towards digital engineering. Planning such an initiative, model organization and arranging ownership for the different types of models is an issue.
- Because architecting focuses on the (technical) product, and not so much on the organization, or services provided by an organization, the link to business seems to be missing. Architecture is rather a result of evolution than driven by business (OPAB instead of BAPO). The Canvas project has identified this gap between enterprise and system architecture. The ArchSkills project [16] also identified the need for architecture governance and management, and did not see it as a responsibility for the architect.
- The ArchSkills project identified overlap in the roles for the platform, systems and solutions architect. Awareness was created that each architect has another 'system of interest' and lifecycle to consider. Apparently the naming 'architect' has quite some status and value in the high-tech industry. In other domains, there is a trend towards splitting roles and responsibilities differently towards a requirements owner, system designer, systems architect and system modeler.
- It seems loss-driven qualities are becoming more important for the high-tech industry. This is reflected by the increased need for (cyber) resilience [11] and concerns about environmental impact. As learned in the Canvas project, often such qualities are analyzed in isolation (for a constituent system) and not from a 'system of systems' perspective. Other domains like railways, automotive and aerospace where systems of systems are more common might offer cross-over opportunities in terms of defining an engineering approach.

Note: Creating technical debt and having a legacy to support might be a consequence of the pragmatic approach to systems engineering. What defines an innovative environment? When should an informal and human-centric approach make a transition towards more formal and systematic approaches? Which approach fits which organization (small scale start-ups versus large and established organizations)? These are all strategic questions that might require enterprise architecting and systems engineering.

(Preliminary) Conclusions

The high-tech industry way of working in the Eindhoven area has evolved towards highly specialized and organization-specific approaches. This amount of customization makes it difficult to scale and transfer domain knowledge quickly. People working in the industry typically tend to stay, because their in depth knowledge, experience and status will not be applicable in other domains. Job descriptions are more or less unique and as a consequence organizations have a hard time finding new people that can fill these posts.

Retaining existing and developing the future workforce is impossible if there is no room to grow as a systems engineer. For this growth, being exposed to multiple domains and systems of systems challenges is considered to be a key ingredient [9]. The closed community in Eindhoven and specific approaches per organization makes it difficult to develop SE capabilities and grow as an organization. Professionals joining an organization first need to become familiar with all 'seven samurai', and for that depend highly on (implicit) knowledge and experience of their colleagues [8]. The increased complexity of high-tech systems combined with the limits an individual can comprehend may require a change in the Dutch approach to engineering high-tech systems.

Systems Engineering and Enterprise Architecting standards are expected to bring value to:

1. TNO-ESI and its industry and implementation partners; by providing a reference framework for developing, implementing, and sustaining domain-specific approaches to architecting and engineering high-tech systems
2. TNO, academic, industry, and implementation partners, as shared discipline-specific knowledge assets for (continuous) learning and knowledge management

By adopting a generic approach to systems engineering based on the system complexity, the high-tech industry might become more successful in coping with its challenges. Tailoring of standards towards the domain should ensure that life cycle processes are effective, regardless of the system's complexity. Other domains have good and bad experiences tailoring these standards, both can be of value to the high-tech industry. For each organization, there will remain a specific balance between the level of standardization versus customization, in order to improve efficiency, risks reduction, quality, and scalability.

Quote: A framework is a logical structure for classifying and organizing complex information. In any given domain, a reference framework provides a common backplane for consistency, collaboration, sharing, and reuse. With an appropriate reference framework, the work of individual projects, programs, divisions and partners will be coordinated with just enough formality to ensure that the many moving parts can fit together when and where needed. [ISO IEC IEEE 24641].

Recommendations

The PMC team Systems Architecting/Systems Engineering already identified some key areas of interest to collaborate on. Digital transformation (also described in Chapter 3) is considered to be an important enabler for developing complex systems of systems and product lines [6]. Many industry partners (TNO included) seem to struggle getting started with this transition. Difficulties are seen in defining the purpose, taking the lead, and organizing and allocating ownership of the different types of models.

The following three industrial challenges are identified for which a model-based approach might bring a valuable opportunity when considering the high-tech domain:

1. Improving system qualities and managing digitalization for value-added services in highly complex and adaptive systems (of systems) is a crucial challenge. Loss-driven qualities like safety, security, and sustainability are increasingly becoming critical drivers for upgrading these systems to stay competitive. Loss-Driven Systems Engineering (LSDE) approaches can provide opportunities addressing this challenge.
2. Managing variability for solution providers of complicated (sub)systems and platform modules involves balancing standardization and customization to meet diverse customer needs while maintaining efficiency and scalability. Product Line Engineering (PLE) approaches can provide opportunities to achieve this balance by enabling systematic reuse of core assets and facilitating the management of product variations.
3. Managing integration for machine suppliers with well-defined system elements is still an ongoing challenge, especially when it comes to supporting design, make, or buy decisions and organizing systems engineering within the supply chain. Requirements Engineering and Management (RE&M) approaches can provide opportunities to streamline these processes and ensure successful integration.

In order to evaluate an approach to SE/SA that addresses a challenge like described above, a scope needs to be defined. Are we only considering the architecting part, or do we also look at design and integration activities? And to what extent are management and governance activities part of the approach? The ISO 15288 standard provides a framework for all these lifecycle processes. This framework can be used to structure the activities we want to include in each approach. The intention is to define an informal, semi-formal and formal approach for each challenge and test it out for a simple, complicated and complex system, respectively. At some point, the amount of information to be managed during the lifecycle of such a system will become so much, a transition towards a more formal approach is needed to collaborate in an effective way.

Recommendations:

- Agree on the scope of each approach and what to use as a reference
- Make sure to have representative cases for each challenge and associated domain experts available

- Make sure to have a digital environment and associated modeling experts available for evaluating the (semi) formal approaches
- Start testing the approaches for simple systems, and then continue to more complicated and complex systems, while continuously evaluating and updating the approaches.
- Prepare for a steep learning curve. Break down the work in small steps and take an iterative approach.
- Learning by doing is essential in overcoming the steep learning curve associated with the more formal model-based approaches. Make sure to have an MBSE expert onboard to intervene if necessary.

By progressively building knowledge and skills, integrating tools and processes, and fostering a culture of continuous learning and improvement, a team can effectively master MBSE and leverage its benefits for complex architecting and design challenges. By integrating systems engineering standards into each phase of the learning and implementation process, the team can ensure consistency, reliability, and interoperability in their MBSE efforts.

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Glossary

Term	Type	Meaning
Business	Organization	An organization engaged in the trade of goods, services, or both to consumers.
Complex System	System	A **complex system** has elements, the relationship between the states of which are weaved together so that they are not fully comprehended, leading to insufficient certainty between cause and effect.
Complicated System	System	A **complicated system** has elements, the relationship between the states of which can be unfolded and comprehended, leading to sufficient certainty between cause and effect.
Digital Twin	Model	A digital twin is a related yet distinct concept to digital engineering. The digital twin is a high-fidelity model of the system which can be used to emulate the actual system. An organization would be able to use a digital twin to analyze design changes prior to incorporating them into the actual system.
Model	Entity	An abstract representation of an entity or collection of entities that provides the ability to portray, understand or predict the properties or characteristics of the entity or collection under conditions or situations of interest.
Model-based systems engineering	Entity	Model-based systems engineering (MBSE) is the formalised application of modelling to support systems engineering (SE) throughout the whole life cycle of an System of Interest (SoI). MBSE is a subset of digital engineering (DE). MBSE supports the SE activities of requirements, architecture, design, verification, and validation. These models would have to be connected to the physics-based models used by other engineering disciplines such as mechanical and electrical engineering.
Organization	Entity	A group of people and facilities with an arrangement of responsibilities, authorities and relationships.
Process	Entity	Set of interrelated or interacting activities that transform inputs into outputs.
Product	Entity	Output of an organization that can be produced without any transaction taking place between the organization and the customer.
Project	Entity	An endeavor with defined start and finish criteria undertaken to create a product or service in accordance with specified resources and requirements.
Service	Entity	Output of an organization with at least one activity necessarily performed between the organization and the customer.
Simple System	System	A **simple system** has elements, the relationship between the states of which, once observed, are readily comprehended.
System	Entity	Arrangement of parts or elements that together exhibit a stated behaviour or meaning that the individual constituents do not.