A Guideline for the Implementation of Model-based Systems Engineering

Master's Thesis No. 0060

Scientific Thesis for Acquiring the
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of the Technical University of Munich.

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Declaration

I assure that I have written this work autonomously and with the aid of no other than the sources and additives indicated.

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Project Definition (1/2)

Initial Situation

As systems grow in scale and complexity, traditional engineering practices deployed in multidisciplinary development programs reach their limits. Along with the advancing digitalization of the workplace, this drives the need for organizations to adopt an improved, digital product development methodology. Model-based systems engineering (MBSE) is seen as a promising source of such methodologies, leveraging the capabilities of models and systems thinking to deal with complex products and development efforts. Although there are numerous papers listing the benefits of MBSE, its value still needs to be convincingly proofed in practice to fast-track its adoption. Implementation and design of a beneficial model-based development environment are complicated tasks as such an environment is a complex sociotechnical system deployed in diverse contexts.

Goals

The overall objective of this work is to enable the assessment and effective design of model-based development environments, enabling organizations to adapt to the needs of increasingly complex products through making use of new digital opportunities. This should result in improved engineering environments serving society by delivering better systems cheaper and faster. Therefore, the aim of this thesis is to support practitioners in improving their development programs through assisting them in making beneficial use of MBSE. To accomplish that, this thesis identifies and maps desired program improvements to capabilities of MBSE methodologies and outlines design recommendations in a framework for the assessment and design of model-based development environments. For a proof-of-concept and to demonstration its potential, the framework is validated in a practice-inspired case study.

Project Definition (2/2)

Contents of this Thesis:

- Initially estimate the potential of MBSE in an organization
  - specify which factors should be considered for estimation
  - estimate the potential on an organizational level
- Identify excellence improvements
  - create an overview of excellence improvements achievable through MBSE
  - combine theoretical and practically achieved excellence improvements
- Examine success measures
  - couple the excellence improvements to suitable metrics
  - describe the measurement of appropriate metrics
  - indicate MBSE specific effects to support the successful deployment of MBSE in an organization
- Determine environment structure and influence on MBSE capabilities
  - the structure of the development environment is to be made transparent to understand the impact of MBSE
  - merge different views on the development environment
  - ensure applicability and authenticity of a generic environment
- Explore MBSE transformation approaches
  - explore the influence of different factors of the approach to support the decision for a suitable and successful transformation
  - exercise a demonstrative example

An accurate elaboration, a comprehensible and complete documentation of all steps and applied methods are of particular importance.

The work remains a property of the Laboratory for Product Development and Lightweight Design.

Project Note

Master's Thesis	No. 0060
Supervisor	Jakob Trauer
Partners in industry/research	Dr. Eric Rebentisch, Consortium for Engineering Program Excellence, Massachusetts Institute of Technology
Time period	01.05.2019 - 16.09.2019

The dissertation project of Mr. Jakob Trauer set the context for the work presented. My supervisor Mr. Jakob Trauer mentored me during the compilation of the work and gave continuous input. We exchanged and coordinated approaches and results biweekly.

Publication
I consent to the laboratory and its staff members using content from my thesis for publications, project reports, lectures, seminars, dissertations and postdoctoral lecture qualifications.

Signature of student: ______________________________________

Signature of supervisor: ______________________________________

Content

1 Introduction

In this chapter the initial situation and problem is described (1.1), leading to the research question, objectives and requirements on a solution statement (1.2). How these objectives are pursued is depicted in the following subchapter (0), covering the used research methodology and statistical analyses. The chapter closes with the thematic classification and structure of the thesis (1.4).

1.1 Initial situation and problem description

As systems grow in scale and complexity, traditional engineering practices deployed in multidisciplinary development programs reach their limits (Sheard et al., 2015, p.1). This, along with the advancing digitalization of the workplace, drives the **need** for organizations **to adopt an improved, digital product development methodology** (Madni & Sievers, 2018, p.1).

Model-based systems engineering (MBSE) is seen as a promising source of such methodologies (Huldt & Stenius, 2019, p.135), leveraging the capabilities of models and systems engineering to deal with complex products and development efforts. Especially, **organizations** dealing **with complex products and development programs tend to rely on MBSE** in their efforts to become digital, as shown in Figure 1-1.

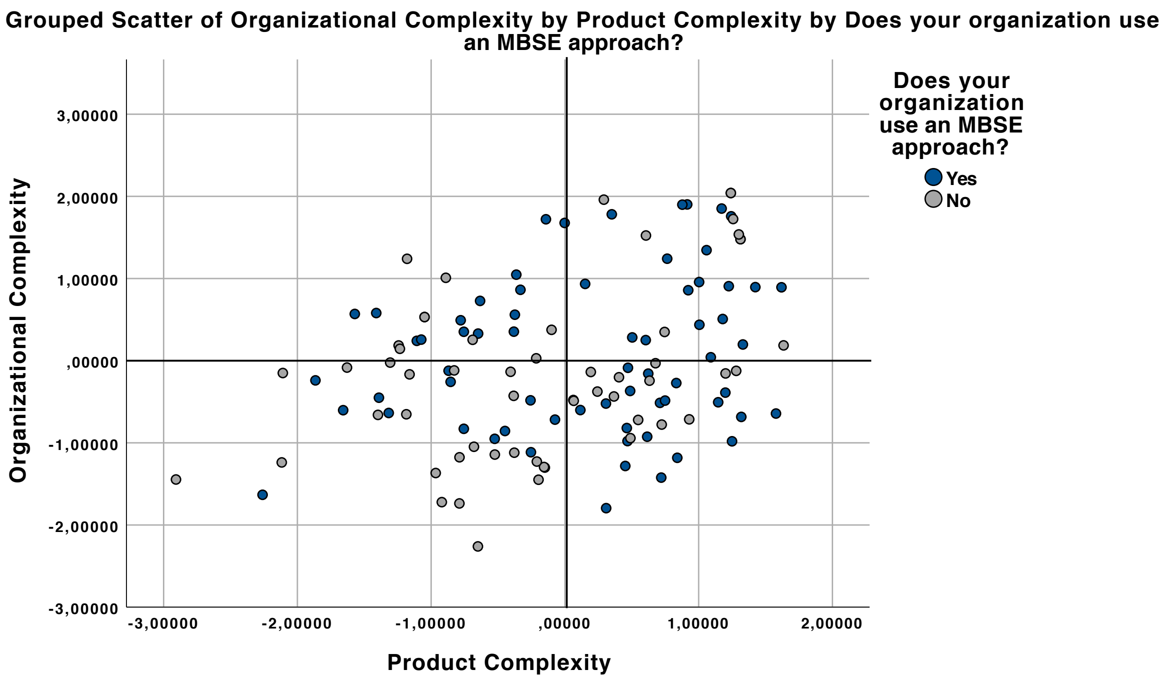

Figure 1-1: Organization's usage of MBSE over organizational and product complexity, as further explained in section 3.3

A majority of engineers thinking that MBSE should be implemented in their organization work for one of the grey-colored organizations, which do not use an MBSE approach today (52 % of 347). This data, gathered in a survey conducted in the scope of this thesis (see subchapter 3.3), indicates a **growing number of organizations facing the adoption of MBSE** in the near future.

An explorative literature study has shown that organizations currently facing the adoption of MBSE struggle with five generally occurring problems. Each problem is briefly described in this subchapter.

Complex methodology assessment

Digital transformation methodologies are manifold (e.g.: Industry 4.0, MBSE, Digital Twin) and so are MBSE approaches. According to (INCOSE, 2007, p.35), *"many companies and organizations that attempt to define their internal processes according to these standards and models are doing so for the first time"*. On top of that, (Reichwein & Paredis, 2011, p.3) identifies a lack of reports on how these methodologies perform and compare to each other, making choosing one of them difficult. According to him, **especially small and medium-scale enterprises struggle with assessing methodologies**, resulting in a weak number of applications. Haberfellner et al. (2019) emphasize the same aspect in their book's preface, by stating that systems engineering (and thereby MBSE) has its roots in large organizations, leading to extensive and difficult to understand methodology concepts. They motivate the creation of *"structured, common-sense, and transparent approach[es]"* focusing on the basics, *"that can be understood by a large range of individuals and not only by highly skilled technical professionals"* (Haberfellner et al., 2019, p.V).

Differing understandings of MBSE capabilities

What complicates the assessment of MBSE is that MBSE is a rather young discipline (Reichwein & Paredis, 2011, p.1). Differing sources describe **differing understandings of the capabilities and values of the methodology**. The International Council on Systems Engineering - INCOSE (2014, p.49) formulated its vision for MBSE as being a *"standard practice and [...] integrated with other modeling and simulation as well as digital enterprise functions"* in 2025. To enable MBSE to become a standard practice the *"value proposition needs to be convincingly demonstrated [...] to system acquisition managers, program managers, and systems engineers for large-scale projects covering different real-world systems of interest"* (Madni & Sievers, 2018, p.187).

Too general or not transferable metrics on MBSE

Currently two major kinds of publications exist about the value of MBSE: The first kind of publications discusses the qualitative value and theoretical benefits of MBSE (Madni & Purohit, 2019; Walden et al., 2015). The other kind compares different metrics of an organizational setting before and after the introduction of MBSE (Krasner, 2015; Scheeren & Pereira, 2014). Consequently, while the first are **transferable between different settings**, they are **too general to support the management of the MBSE implementation** in a specific, organizational setting **and vice versa** for the latter.

Patchwork environments not fulfilling expectations

Today, most transformation approaches are not orchestrated by a clear and governing value proposition linked to an aligned methodology. This leads to digital **patchwork environments** (Lineberger, 2019; Long, 2018), **not fulfilling the expectations** towards the digital transformation. Assessment and design of a beneficial model-based development environment are complicated tasks as such an environment is a complex sociotechnical system deployed in diverse contexts. However, the above described shortcoming limits an organizations potential to select effective building blocks of its MBSE methodology.

Lack of guidelines on how to implement MBSE

From 356 engineers questioned in a survey (see section 3.3.3) what makes it difficult to convince others of the value of MBSE for their organization, 59 % stated that a **lack of guidelines on how to implement MBSE** makes this task difficult. This indicates that the implementation of MBSE is the key challenge for the participants of the survey and that future work should focus on providing guidelines facilitating the implementation of MBSE.

The five problems – complex methodology assessment, differing understandings of MBSE capabilities, too general or not transferable metrics, patchwork environments not fulfilling the expectations, and a lack of guidelines on how to implement MBSE – described in this subchapter are addressed in this thesis. The next subchapter picks up the problem description in the formulation of the research question and objectives as well as requirements towards a solution statement.

1.2 Research question and objectives

The research question results from the five shortfalls described in the problem description and implicates the current state of research. It represents the core of this thesis:

How can Model-based Systems Engineering be meaningfully and successfully implemented, to improve the excellence of existing, complex product development environments?

To contribute meaningful insights to and answer the research question the it is split into five research objectives, which are covered in the chapters of this thesis:

Research objective (1): Initially estimate the potential of MBSE in an organization

In order to prepare the management decision whether MBSE should be adopted in the respective organization, the potential of MBSE has to be initially estimated. As MBSE capabilities and organizations are diverse, a general estimation should be based on standard characteristics. Also, these characteristics should be at hand to minimize the estimation effort.

Research objective (2): Identify excellence improvements

MBSE is currently used in a variety of applications. There is no broad overview of the excellence improvements (improvements to the efficiency and effectivity of product development) achieved through MBSE capabilities, which an implementation offers. This hinders the justification and purposeful implementation of MBSE. The identified excellence improvements should be industry-neutral and realizable in product development.

Research objective (3): Examine success measures

To steer and prove the success of the implementation effort the excellence improvements should be coupled to suitable metrics. This research focuses on finding exemplary metrics, as these metrics vary highly with the respective organizational situation. The metrics should capture the value of MBSE and should reflect improvements.

Research objective (4): Determine environment structure and influence on MBSE capabilities

The development environment, in which the developer works, is the center point of the MBSE transformation. Therefore, the structure of this central environment is to be made transparent to understand the impact of MBSE. The achieved understanding of the environment should guide the design of successful MBSE environments. The developed environment structure should include all MBSE-relevant elements and be transferable.

Research objective (5): Explore MBSE transformation approaches

The transformation towards MBSE is changing the current engineering practice to improve these. In order for this transformation to be in line with the pursued improvements, the transformation approach has to be chosen wisely. The influence of different factors of the approach is to be explored to support the decision for a suitable and successful transformation.

Figure 1-2 summarizes the research question and objectives.

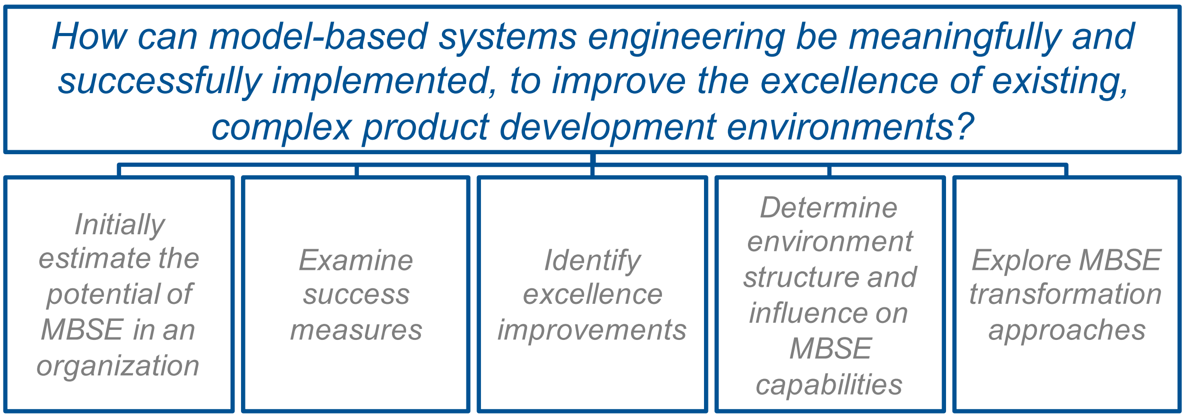

Figure 1-2: Research question and research objectives

Focus and research question highlight the theme of this thesis. The theme is detailed in this section through the definition of **requirements towards a solution statement**. These requirements are deduced from the problem description and research objectives.

A solution statement should support complex, product development organizations in the following activities:

- Assessment of the aptitude for MBSE
- Understanding MBSE capabilities
- Management of the MBSE implementation
- Systematic MBSE transformation of the environment
- Applying a structured MBSE transformation approach

Each of these activities should be supported in an approach possessing the five standards for the quality of conclusions elaborated by Miles et al. (1994, pp.278-280):

Objectivity/Confirmability/Reproducibility

This characteristic concerns the way the solution approach has been worked out. It evaluates the reproducibility of results drawn from the presented data, independent of the researcher.

Reliability/Dependability/Auditability

The central question regarding this characteristic is: Have things been done with reasonable care? Again, focusing on the way, the solution approach has been worked out. Although, this time the question is not whether it can be carried out the same way, but if it should be carried out the same way.

Internal Validity/Credibility/Authenticity

Internal validity is determined through asking if the presented approach makes sense. That means it is free from internal contradictions and that there are no plausible alternative conclusions than the presented ones.

External Validity/Transferability/Fittingness

External validity regards the assumptions used to create the approach. They determine how flexible the approach fits different contexts. Therefore, it is a measure for the scope of application and reasonable generalization.

Utilization/Application/Action Orientation

The final criterion for the approach is its applicability. It clarifies if the approach meets the target groups' problem understanding and if it is sufficiently supporting the necessary actions to cope with the problem.

Table 1-1 summarizes the requirements on a solution.

Table 1-1: Summary of requirements, consisting of capabilities and quality standards

Supported activities	Assessment of the aptitude for MBSE
	Understanding MBSE capabilities
	Management of the MBSE implementation
	Systematic MBSE transformation of the environment
	Applying a structured MBSE transformation approach
Quality standards	Reproducibility
	Reliability
	Authenticity
	Transferability
	Application

The next subchapter depicts the research methodology matching the objectives and requirements presented in this subchapter.

1.3 Research methodology and contribution

The research methodology used in this thesis is based on the Design Research Methodology introduced by Blessing and Chakrabarti (2009, p.15). Figure 1-3 shows the stages and goals of their methodology framework as well as the basic means used in the creation of this thesis.

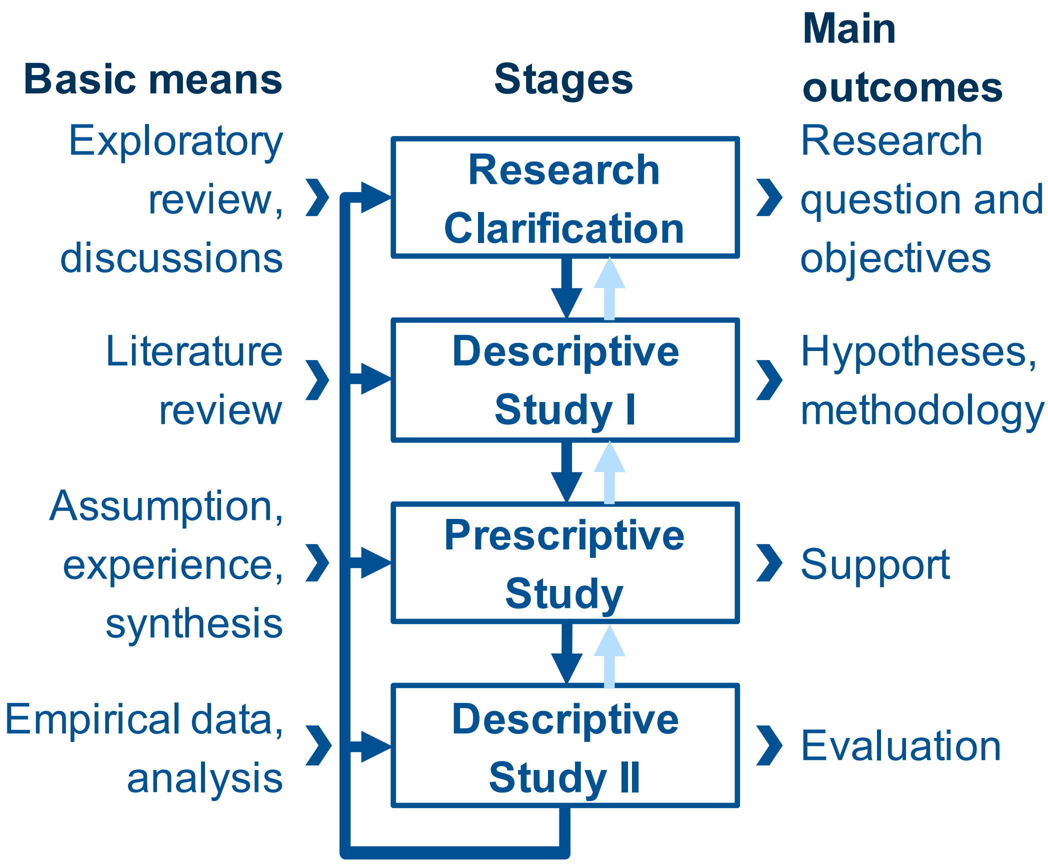

Figure 1-3: Design Research Methodology framework adopted from Blessing and Chakrabarti (2009, p.15)

According to Blessing and Chakrabarti (2009, p.15) the focus in research clarification is *"to formulate a realistic and worthwhile research goal"*. This was done through an **exploratory literature review** as well as **discussing several topics** in conversations and lectures.

The second phase coveres the first descriptive study also referred to as literature and prior studies. Blessing and Chakrabarti (2009, p.16) state that *"the intention is to make the description detailed enough to determine which factor(s) should be addressed to improve task clarification as effectively and efficiently as possible"*. As the title indicates, the initial **literature review was expanded** to cover the state of the art on the research objectives. This review formed the basis for the **formulation of hypotheses and choosing the appropriate research methodology** for each research objective.

"In the Prescriptive Study (PS) stage, the researchers use their increased understanding of the existing situation to correct and elaborate on their initial description of the desired situation". Thereby, the design support is developed. In the final step the researches turn to *"the Descriptive Study II (DS-II) stage to investigate the impact of the support and its ability to realise the desired situation"* (Blessing & Chakrabarti, 2009, p.16).

The third and fourth phase, prescriptive study and descriptive study have been carried out specific to the research objectives in this thesis.

For the initial estimation of the potential of MBSE in an organization the prescriptive study consisted of the **creation** of the survey questionnaire **and** the **realization of the survey**. The second descriptive study was the **description and interpretation of** significant analyses **results**.

The prescriptive study for identifying excellence improvements clustered and aggregated **improvements** identified **in literature**. These were **presented to experts in the interviews** and documented, forming the second descriptive study.

To examine success measures, the measurement of the MBSE capabilities has been **prescribed by the experts in their interviews**. Subsequently they were **documented and reflected** in terms of meeting the requirements in the second descriptive study.

The prescriptive study for the environment structure was based on a **literature study**, which was used to determine an influenced environment structure. This environment structure has been **presented to the experts in the interviews** and their feedback was documented in the second descriptive study.

For the final research objective, exploring MBSE transformation approaches, a prescriptive study in the form of the **design of an implementation guideline** has been carried out. The related descriptive study covered a **practice-inspired case study** for verification and the validation regarding key factors.

Table 1-2 summarizes the basic means used in the prescriptive study and second descriptive study for each research objective.

Table 1-2: Basic means used in the prescriptive and second descriptive study for each research objective

	Initially estimate the potential of MBSE in an organization	Identify excellence improvements	Examine success measures	Determine environment structure and influence on MBSE capabilities	Explore MBSE transformation approaches
Prescriptive study	Survey and analysis	Literature study	Expert interviews	Literature study	Implementation guideline design
Descriptive study II	Interpretation	Expert interviews	Key factors validation	Expert interviews	Practice-inspired case study, key factors validation

To conclude this subchapter on research methodology, the **statistical analyses** conducted in section 3.3.3 are briefly explained. It is assumed, that the reader understands basic statistical concepts like significance, mean, and standard deviation.

Pearson's chi-squared test

Pearson's chi-squared test is used to test if there is a relationship between two categorical variables. Therefore, a crosstable is created, containing all categories with the observed counts. These observed counts are compared to the expected counts for this category. The Parsons's chi-squared statistic (χ^2) adds up all these standardized deviations, as shown in formula 1.1 and 1.2 (Field, 2009, p.688), with i being the rows and j the columns of the crosstab.

$$\chi^2 = \sum \frac{(observed_{ij} - expected_{ij})^2}{expected_{ij}} \qquad (1.1)$$

$$expected_{ij} = \frac{row\ total_i \times column\ total_j}{N} \tag{1.2}$$

Independent t-test

An independent t-test compares the two means of two different samples to check for significant differences. It uses the means ($\bar{X}$), standard deviations (s), and sample sizes (n) to calculate the value of t, which is the difference of means divided by an estimate of the standard error between the samples, as shown in formula 1.3 (Field, 2009, p.336).

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_p^2}{n_1} + \frac{s_p^2}{n_2}}} \tag{1.3}$$

Because the sample sizes are different for the survey conducted in this thesis, the sample variance is weighted by the sample size, as shown in formula 1.4 (Field, 2009, p.336).

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \tag{1.4}$$

To assess the effect of the difference in means, Pearson's r is calculated as an effect size using formula 1.5 containing the degrees of freedom (df) (Rosnow and Rosenthal (2005) in Field (2009, p.332)).

$$r = \sqrt{\frac{t^2}{t^2 + df}} \tag{1.5}$$

Thereby, values of 0,1 represent a small effect, 0,3 a medium effect, and 0,5 a large effect (Field, 2009, p.173).

Analysis of variance (ANOVA)

When the influence of multiple samples on the mean of a dependent variable is to be analyzed, ANOVA is used. The F-ratio is calculated by dividing the variation explained by the model (model mean squares) by the variation caused by unsystematic factors (residual mean squares), as shown in formula 1.6 (Field, 2009, pp.357-358).

$$F = \frac{MS_M}{MS_R} = \frac{\frac{SS_M}{df_M}}{\frac{SS_R}{df_R}} = \frac{\frac{\sum n_k(\bar{x}_k - \bar{x}_{grand})^2}{df_M}}{\frac{\sum (x_{ik} - \bar{x}_k)^2}{df_R}} \tag{1.6}$$

With df_M and df_R being the degrees of freedom of the model (Number of samples - K) and the residuals (N – K). The grand mean ($\bar{x}_{grand}$) is the mean of all scores for the variable, independent of the sample. The F-ratio indicates an effect in the data, to find out which samples caused the effect, post hoc analyses have to be carried out (Field, 2009, p.375). E.g. comparing the mean of two groups with the t-test.

Omega-squared is calculated as shown in formula 1.7 (Field, 2009, pp.356, 389), to get an idea of the effect size.

$$\omega^2 = \frac{SS_M - (df_M)MS_R}{\sum (x_i - \bar{x}_{grand})^2 + MS_R} \tag{1.7}$$

According to (Kirk (1996) in Field (2009, p.390)), a ω^2 value of 0,01 represents a small, 0,06 a medium, and 0,14 a large effect size.

Bivariate correlation

Pearson's correlation coefficient is used to examine relationships between numeric variables. The coefficient is also used to measure the effect size, as discussed in the independent t-test section. The coefficient is computed by standardizing the covariance of variables, as shown in formula 1.8 for the variables x and y (Field, 2009, p.170).

$$r = \frac{covariance_{xy}}{s_x s_y} = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{(N-1)s_x s_y} \quad (1.8)$$

The covariance is the average sum of combined deviations from the means of the variables. The covariance is standardized through dividing it through the product of the variable's standard deviations.

The value of r lies between +1 and -1, with +1 representing a perfect positive relationship between the variables and -1 representing a perfect negative relationship (Field, 2009, p.170). Meaning that the variables are direct or indirect proportional to each other. A value of 0 indicates no relationship between the two variables.

Principal component analysis (PCA)

Principal component analysis is used to reduce the dimension of data, specifically the number of variables. Therefore, the correlation coefficients between the variables are used. How these are computed is shown in formula 1.8 in the previous section. The R-matrix (R) is a matrix consisting of the correlation coefficients between the variables. It has ones on the diagonal, as every variable is perfectly positive related to itself. This matrix is used to find the components, which are variable groups that cluster together in a meaningful way. Therefore, the eigenvalues of the matrix and eigenvectors for each eigenvalue are calculated. The eigenvectors provide the component loadings for each variable and component. The related eigenvalue is a measure for the component's importance. All the component loadings respectively eigenvectors make up the component matrix (A). The component matrix is then used to calculate the component score coefficients matrix ($B = R^{-1}A$). These are coefficients enabling us to calculate the component score for a given set of variable values (Field, 2009, pp.638-665).

If an oblique rotation is used, which is the case if there is reason to believe that the components are correlated, two matrices represent the component matrix (A). First, the pattern matrix (A_p) contains the factor loadings and is therefore comparable to the component matrix. Second, the structure matrix (A_s) should be reported, as values in the pattern matrix might be suppressed because of the interrelations between components. The structure matrix can be calculated by multiplying the pattern matrix with the correlation matrix between the components ($A_s = A_p R_c$) (Field, 2009, p.666).

The percentage of variance explained by the components is a measure for the quality of the principal component analysis and the explanation capability of each factor. The more variance is explained, the better the analysis has been carried out. The two main influencing factors on this measure are the number of components derived and the rotation used.

The following subchapter gives an overview of the related fields of research and the thesis structure.

1.4 Thematic classification and structure of the thesis

In this subchapter, the thematic classification of this thesis discusses the fields of science related and partially covered in this thesis, while the structure of the thesis orientates and guides the reader's reading.

Systems and **digital engineering** are the central fields of science influencing this thesis, as model-based systems engineering unifies aspects of both engineering fields and most contributions, like the development environment structure and the guideline to MBSE implementation, advance these fields. As the focus of the thesis is on the implementation of MBSE in **product development**, research and concepts from this field are also represented and extended. The same can be claimed for **organizational transformation**, which is a subdiscipline of management. With the organizational aspect, some aspects of **sociotechnical systems** are incorporated into parts of the thesis. Figure 1-4 visualizes the related and covered fields of research for this thesis.

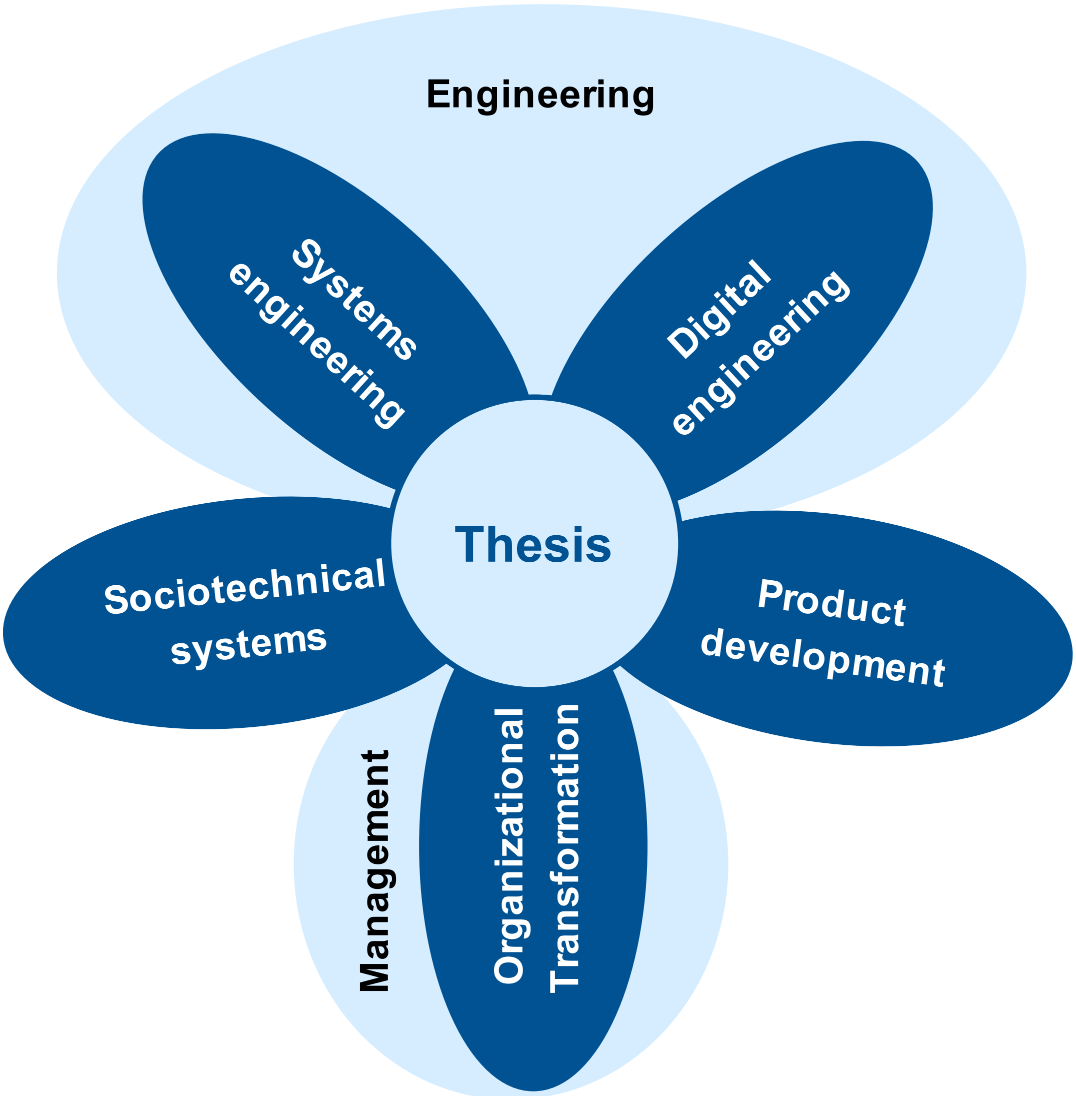

Figure 1-4: Classification of the thesis in related fields of research

Within the thesis, the content is structured as follows.

In the **first chapter**, the initial situation and current problems have been described. Next, the research question, objectives, and requirements on a solution statement have been depicted. A research methodology matching the objectives and requirements has been outlined in the following subchapter. The chapter closes with the thematic classification and structure of the thesis in this subchapter.

The **second chapter** depicts the knowledge basis for this thesis. First, the fundamentals cover the main concepts and definitions. Second, the existing work subchapter describes the current state of research on each research objective. The last subchapter summarizes derived directions from the state of the art.

The following, **third chapter** depicts the design of the guideline. Therefore, literature studies regarding MBSE potential, capabilities, and environments are elaborated. Data from a survey conducted by the author is analyzed for further insights. Finally, the conclusions from expert interviews regarding MBSE objectives, metrics, and environment are outlined. The chapter ends with a summary of contributions from each investigation.

This summary preludes the **fourth chapter**, which outlines a complete cycle of the guideline. The steps of the guideline – assess MBSE potential, analyze environment, set focus, design environment, define transformation, and transform as well as validate – are described in theory. The cycle is again summarized in the last subchapter.

The theoretically introduced guideline cycle is verified and validated in the **fifth chapter**. For the verification a practice-inspired case study is used and described in the first subchapter. The validation in the proceeding subchapter uses key factors in the assessment of the guideline. The chapter closes with the discussion of obtained results and the reflection of the applied methodology.

The last, **sixth chapter** includes conclusion and outlook. The contribution and approach of the thesis is summarized in the conclusion. Finally, further research opportunities related to the contributions of this thesis are elaborated in the outlook.

The entire structure of the thesis is visualized in Figure 1-5.

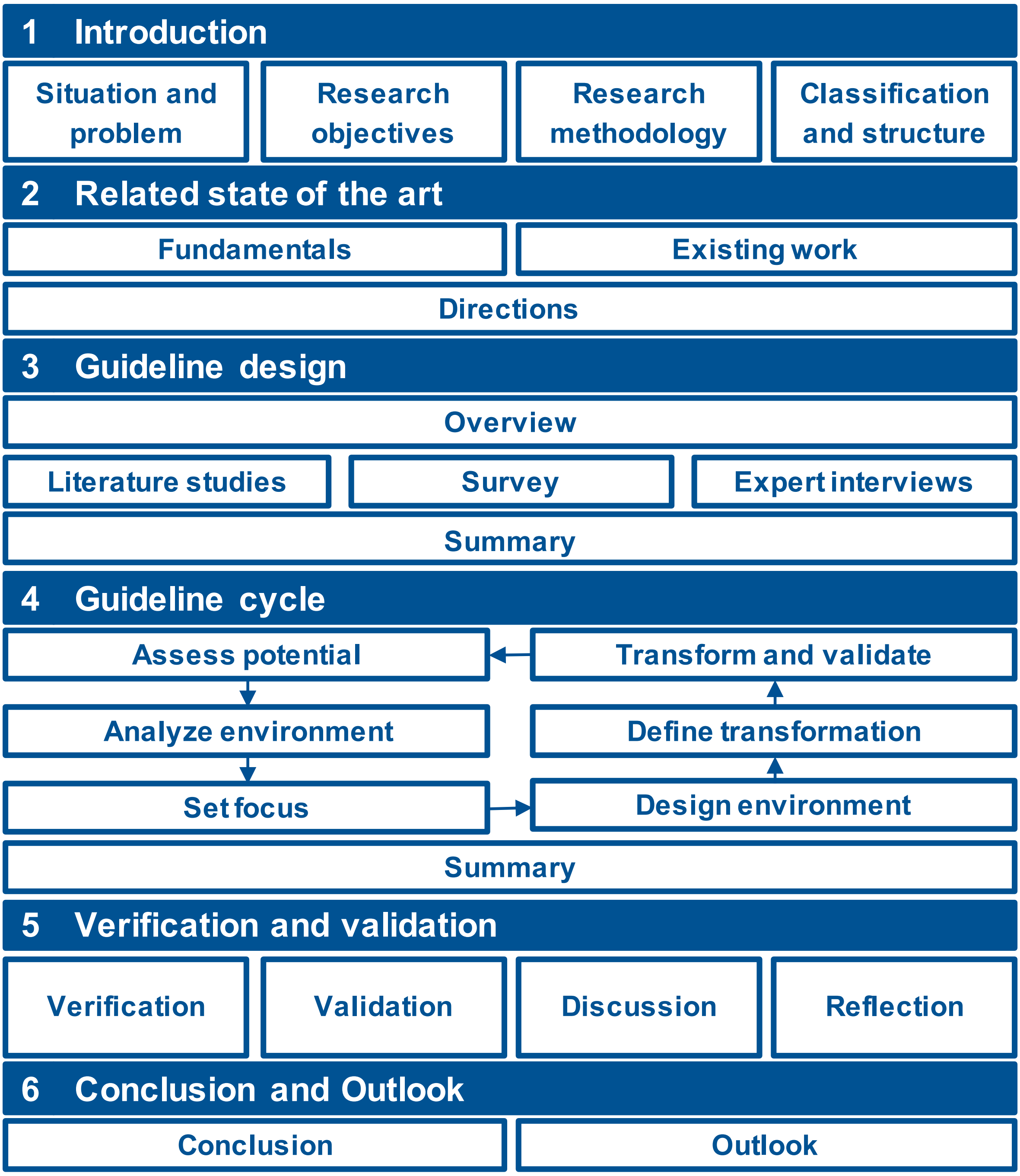

Figure 1-5: Structure of the thesis

2 Related state of the art

This chapter presents the state of the art related to the problem description and research focus examined in the previous chapter. Therefore, the next subchapter introduces the fundamental concepts used in this thesis. After that, the second subchapter of this chapter gives an overview of and assesses the existing works covering the five research objectives depicted in subchapter 1.2. The chapter closes with a subchapter on directions from the state of the art, triggering the research documented in the following chapter.

2.1 Fundamentals

This subchapter clarifies fundamental concepts and points out the basic understanding building the basis for the work depicted in this thesis. The subchapter will start with the most extensive concept and will work its way down to the basic definitions.

2.1.1 Systems engineering

Systems engineering is a very broad field of research and practice. Completely defining it goes beyond the scope of this thesis. Therefore, this section sticks to the necessary definitions and points out that there are more and more rigorous definitions in existence.

For the context of this thesis, **systems engineering** is defined as **interdisciplinary field between engineering and management focusing on applying systems thinking**. INCOSE (2019) defines systems engineering in more detail as *"an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem [...]"*.

This broad and ambiguous definition lead to slightly differing understandings and practices of systems engineering. What they all incorporate are a **holistic view and systems thinking**, as indicated by the proposed definition. Using these two differentiation factors, **systems engineering techniques** can be regarded as the **use of systems thinking and a holistic view to enable the realization of successful systems**.

To explain the term systems thinking, a **system** has to be defined first. Shishko and Aster (1995) in Oliver et al. (2009, p.1363) define a system as ***"a set of interrelated elements which interact with one another in an organized fashion toward a common purpose"***. Every system is an element of a more comprehensive system and every element of a system is again a system. The system is separated from its environment through a consciously drawn system boundary (Walter, 2018). Coming back to **systems thinking**, it becomes clear that it denotes the **application of the system concept** outlined above **to the real world**.

2.1.2 Model

The second aspect covered by MBSE are models. To define a **model**, this thesis relies on the model definition by Stachowiak (1973). According to this, a model is a **representation**

covering only relevant attributes of its original and is restricted to recognizing subjects, certain timeframes as well as operations. This general definition emphasizes three key characteristics of models, which will be discussed briefly.

First, there is the **representation** or reproduction **characteristic**, relating the model to an original, which can again be a model. Most of the time, the requirement is to represent the original as accurately as possible (Stachowiak, 1973, p.131).

Second, although accurately describing the original, the model does not cover all its attributes, but only the ones identified as relevant by the modeler and/or model user. This summarizes the **abbreviation characteristic** (Stachowiak, 1973, p.132).

The third and last characteristic is the **pragmatic characteristic**, which is threefold. The general conclusion is that a model is not per se definitely assigned to its original. They represent the original only (1) for certain recognizing and/or acting subjects, (2) within specific timeframes, and (3) restricted to particular theoretical or practical operations (Stachowiak, 1973, p.133).

Especially the last characteristic should be kept in mind to reflect the appropriate use of models and assess their capabilities.

One model characteristic which is vital to most use cases of models in MBSE and has not been itemized above is the **representation of relationships between elements**. This is vital as it allows the model to reflect the concept of a system and differs the model from a document or diagram. While a diagram can visualize relationships between the elements, the model actually incorporates these relationships (Delligatti, 2014, p.3). For example, a screenshot of your computer's file manager shows your files and relationships between them, while the file manager itself incorporates and uses these relationships. This is an important distinction, as the definition given above would categorize both as models, although only the real file manager enables the desired capabilities of e.g. tracing a certain file. This distinction has to be considered when talking about models in MBSE, as in common practice diagrams are misnamed as models, but most **MBSE capabilities can only be achieved by sophisticated models meeting this characteristic**. An example closer to engineering and on a more mature level are Computer-aided Design (CAD) models. A general CAD model representing a component in 3D meets all model characteristics, but it is less useful and captures less information than a parametric CAD model.

2.1.3 Model-based systems engineering

MBSE is a fairly young discipline (Reichwein & Paredis, 2011, p.1), which evolved from the Systems Engineering discipline. It is broadly defined as *"the formalized application of modeling to support systems, requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases"* (INCOSE, 2007, p.189). Other definitions highlight the use of models rather than documents in information exchange (Bandecchi, 2019, p.19) and the related thought processes of systems thinking (Long & Scott, 2011, p.65). This demonstrates that the **model-based systems engineering** methodology **incorporates** both aspects of **models** as well as **systems engineering**. These two aspects have been further examined in the previous sections, as they themselves represent manifold concepts. A methodology in the context of this thesis is regarded as *"the application of related processes, methods, and tools* *to a class of problems that all have something in common"* (Bloomberg and Schmelzer (2006) in Estefan (2007, p.3)). Defining MBSE as such a methodology differentiates the understanding of MBSE used in this thesis from MBSE understandings used in other, older publications.

When the concept of MBSE was introduced in 2007 (Friedenthal et al., 2007), its focus was merely on building descriptive system architecture models. Therefore, the Systems Modeling Language (Hause, 2006), based on and sharing some diagrams with the Unified Modeling Language (UML), was introduced by the International Council on Systems Engineering (INCOSE) and the Object Management Group (OMG) (Object Management Group, 2007). **SysML was used as a synonym for MBSE** and is the major subject of many MBSE publications (Delligatti, 2014; Dori & Crawley, 2016; Friedenthal et al., 2015; Friedenthal & Oster, 2017). **Today, MBSE is seen as capable of integrating multiple models along the system lifecycle and various other modeling languages**, like the Object Process Methodology (OPM), are used within the MBSE methodology. INCOSE formulated its vision for MBSE in 2025 as being a *"standard practice and […] integrated with other modeling and simulation as well as digital enterprise functions"* (INCOSE, 2014, p.49).

The modern entitlement makes MBSE a methodology contender for digital transformation efforts, as indicated in the description of the initial situation in subchapter 1.1. On this level, *"**MBSE** is often placed **in the** broader **context of** model-based engineering (MBE)"* (NDIA (2011) in Friedenthal and Oster (2017, p.3)) and **other methodologies** like model-driven development (MDD), model-driven engineering (MDE) or model-based design (MBD). Rather than seeing a hierarchy between these methodologies (*"MBSE enables MBE"*) (Friedenthal & Oster, 2017, p.3) or seeing these terms as interchangeable (Reichwein & Paredis, 2011, p.2), this thesis regards these terms as indicators of the emphasis on the two aspects covered by each of them. For example, model-based systems engineering emphasizes making models the basis of and incorporating systems engineering techniques in engineering. Model-driven development on the other hand, emphasizes a higher maturity level of model usage without incorporating specific techniques and focuses on development, instead of engineering. To decide if these terms can be used interchangeably or if there is a hierarchy between them, all succeeding terminologies, like system engineering techniques, development, and so forth, have to be precisely defined, which they are not. Therefore, this thesis regards these terms only as **indicators of the focused aspects by the methodology**.

Now, that the fundamental concepts of this thesis have been elaborated, the focus of the next subchapter is on depicting the current state of research in MBSE regarding the research objectives. Therefore, it relies on topical literature on these aspects.

2.2 Existing work

A comprehensive literature study was carried out to depict the current state of research. It focused on setting out the current, major scientific contributions towards the five research objectives:

1. MBSE potential estimation
2. Excellence improvement identification
3. Success measure examination

4. Environment structure and influence determination
5. Transformation approach exploration

The starting points of the literature studies were the universities online catalogues, namely Technical University of Munich (TUM) Online Public Access Catalogue (OPAC) and Massachusetts Institute of Technology (MIT) Barton Plus, as well as Google scholar. Also, journals, conference proceedings, and books recommended by other researchers from the MBSE community were reviewed. It was endeavored to find and cite the original sources where possible. Through this practice further interesting aspects in these secondary works were discovered and included as well.

The main keywords and synonyms combined in the search for literature are shown in Table 2-1.

Table 2-1: Search strategy grid covering the main keywords and synonyms used in the literature search

	Keywords				
Synonyms	Model-based systems engineering (MBSE)	Potential	Metrics	Transformation	Environment
	Model-based development (MBD)	Value	Key performance indicators (KPIs)	Adaption	Workplace
	Model-based engineering (MBE)	Benefits	Measures	Implementation	Methodology

As no existing work combines all research objectives, this subchapter gives a detailed depiction of relevant works per research objective.

2.2.1 MBSE potential estimation

A single publication covers the initial estimation of the potential achievable through an MBSE adoption. It is briefly described and assessed regarding the fulfillment of the five criteria for the quality of conclusions from subchapter 1.2: reproducibility, reliability, authenticity, transferability, and applicability.

Economic Analysis of Model-Based Systems Engineering – Madni & Purohit, 2019

Madni and Purohit (2019) conducted an economic analysis of model-based systems engineering. They identified the industries that should derive the most value from the adoption of MBSE. They did so by "*parameterizing the MBSE implementation problem in terms of system complexity, regulatory and operational environment complexity, and system lifespan*" (Madni & Purohit, 2019, p.16). Figure 2-1 shows the results of the study.

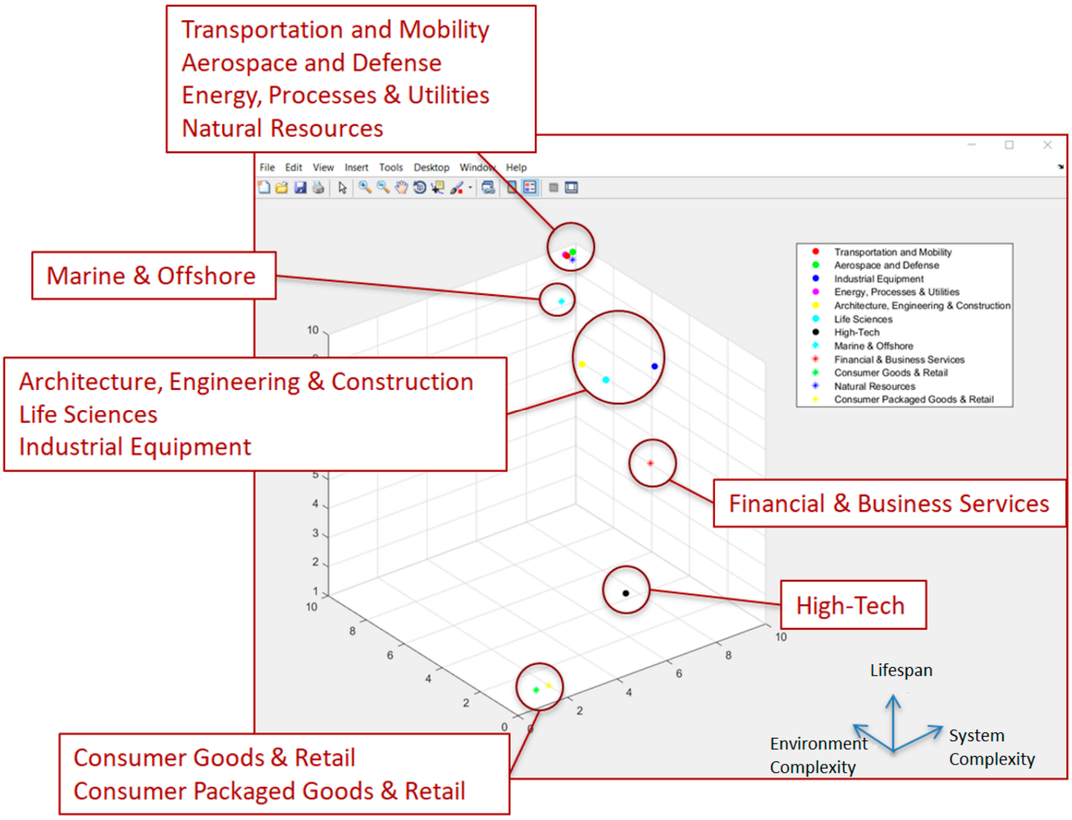

Figure 2-1: Initial potential estimation through categorizing industries along lifespan, environment and system complexity, as visualized in Madni and Purohit (2019, p.16)

Reproducibility of the approach is given but should be improved regarding the values of the characteristics assigned to the respective industry. Reliability of the approach is limited, as there is no justification for the three chosen characteristics. Transferability as well as authenticity of the approach are fully given. The applicability of the approach to companies is limited as the classification along the three characteristics is rather vague.

Table 2-2: Assessment of the potential estimation by Madni & Purohit regarding five quality criteria

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Madni & Purohit, 2019	◕	◑	●	●	◑

2.2.2 Excellence improvement identification

Excellence improvements stemming from an MBSE adoption can be found in eight publications. Excellence improvements are improvements in the efficiency and effectivity of the product development effort. A brief description of the context of the publication is followed by an examination of the mentioned excellence improvements. Each contribution is assessed regarding the fulfillment of the five quality standards defined in subchapter 1.2: reproducibility, reliability, authenticity, transferability, and applicability.

From initial investigations up to large-scale rollout of an MBSE method and its supporting workbench: the Thales experience – Voirin et al., 2015

The excellence improvements derived from the first case study at Thales aerospace are based on a management-initiated initiative "*to analyze existing systems engineering practices, collect ideas and propose and experiment evolutions*" (Voirin et al., 2015, p.2). Each business unit of the company outlined their current practices, difficulties and possible new practices. Comparing these practices, difficulties, and possible new practices revealed that most of the business units share the same kind of engineering practices and challenges. According to Voirin et al. (2015, p.2), these are:

- *In-depth analyzing of customer need, for a clear understanding of its goals, missions and objectives, capabilities etc., and of how the solution would fit its expectations.*
- *Enforcing the place of architects and emphasizing the role of architecture, to improve engineering and system integration efficiency.*
- *Tightening links between architects and engineering specialties (safety, security, performance, interface management...) for consistent, joint decision making.*
- *Increasing continuity and consistency between different engineering levels (system, sub-system and software/hardware).*
- *Detecting definition and architecture design flaws as early as possible, during the design phase rather than in system integration phases.*
- *Improving efficiency of Integration Verification Validation Qualification (IVVQ) by a functional capability-driven strategy, early defined in design phase.*
- *Capitalizing definition and design results, including justifications, in order to improve reuse and product policy.*

The Thales group created and rolled out the Arcadia MBSE method to achieve the enlisted excellence improvements.

Evaluating the excellence improvements, the results presented by Voirin et al. are highly authentic, reliable, and applicable, as they stem from a comprehensive need analysis in the company. Because it was a company-specific analysis, transferability is limited. To further increase reliability and reproducibility, the analysis methods used should be further described by the authors.

Table 2-3: Assessment of the excellence improvements as described by Voirin et al.

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Voirin et al., 2015	◐	◐	●	◐	●

Model-based Advancements at Lockheed Martin Space Systems Company – Dean & Phillips, 2015

At Lockheed Martin Space Systems *"users of MBSD [model-based systems development] extolled the benefits of model-based techniques in software development and other engineering projects"*, where model-based tools have been used for decades and model-based system development approaches have recently been intensified (Dean & Phillips, 2015, pp.1-2). According to (Dean & Phillips, 2015, p.2) users reported that:

- *Details about the system more easily persisted through the lifecycle and provided methods for eliminating duplication and divergence.*
- *Since the behaviors and interfaces of software items are implemented in model constructs ambiguities in the system details were eliminated.*
- *Model-based techniques were also the best solution for managing the linkages of architecture to requirements, requirements to code, test and so on. Dealing with these linkages in the heritage methods were cumbersome and error prone because of the extensive manual effort required to maintain the links.*
- *Model-based techniques have successfully enabled reuse since the design artifacts were more clearly elucidated when compared to heritage methods. Experience also showed that the reuse of design artifacts rather than implemented code artifacts allowed more affordable translation between programming languages.*
- *Model-based techniques were able to reduce defects in final products by increasing the amount of rigor in the artifacts used to communicate to the software implementation team the specific behaviors, relationships, and interfaces necessary.*
- *Another method for reducing defects was in the use of the execution capabilities of certain model-based tools which allowed the design (rather than just the implementation) to be checked against the desired behaviors specified by the customer and user.*

All enlisted excellence improvements are authentic and applicable, as they are again derived from practical users of MBSE. Transferring the results is difficult, as most of the given examples are from software development projects and the results are obtained within a single company. Reproducibility and reliability can be improved through describing the analysis methods used to identify the given excellence improvements.

Table 2-4: Assessment of the excellence improvements as described by Dean & Phillips

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Dean & Phillips, 2015	◐	◐	●	◔	●

Transforming systems engineering through digital engineering – Bone et al., 2018

Bone et al. (2018) describe excellence improvements as they are pursued by the United States Department of Defense (DoD) in its digital transformation. These excellence improvements are based on extensive research on the potential impacts of digital technologies like model-based systems engineering and a government-industry digital enterprise forum. Bone et al. (2018, p.2) describe four major benefits:

- *Improved acquisition – Digital deliverables could improve the government's understanding of a project's status and risk along with allowing a project to validate the contractor's deliverables.*
- *Improved efficiency and effectiveness – A SST [Single-source-of-truth] would reduce time and effort in the performance of existing tasks.*
- *Improved communication; better trade-space exploration; reduced risk – Using ontology-*

based information models to translate and extract useful information among a variety of models and model types could allow for improved communication among specialists. This would enable DoD's goal [...] to establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders.

- *Improved designs and resulting systems and solutions – Being able to understand the impact of requirement and/or design decisions early could help improve the overall system design and identify adverse consequences of the design before committing to a design choice. This would enable the DoD [...] to formalize the development, integration and use of models to inform enterprise and program decision-making through an authoritative source of truth.*

The derived excellence improvements are reproduceable and reliable, as they stem from systematic research. Transferability to development projects with a lower or no involvement of the government is limited. To increase authenticity of the given excellence improvements, they should be further differentiated and described. For example, at improvement three, only the improvement of communication is described, leaving out trade-space exploration and risk reduction. As the improvements have been identified at a government-industry forum, they are applicable, but could be made more applicable through more differentiation and explanation.

Table 2-5: Assessment of the excellence improvements as described by Bone et al.

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Bone et al., 2018	●	●	◑	◑	◕

Digital System Models: An investigation of the non-technical challenges and research needs – Reid & Rhodes, 2016

As Bone et al., Reid and Rhodes (2016) describe excellence improvements that are pursued by the United States Department of Defense in its digital transformation. The four improvements are based on literature research and are according to Reid and Rhodes (2016, p.3):

- *Increased reuse of technical data and models from one project to another, as well as from one stage of a project to another stage of the same project (reduces stove-piping) [(Zimmerman, 2015a)]*
- *More rapid and cheaper cycling of design concepts in a form of virtual prototyping [(Zimmerman, 2015b)]*
- *Better analysis and comprehension of complicated systems [(Zimmerman, 2015b)]*
- *Reversal of the trend of outsourcing technical knowledge from the DoD to contractors and industry partners [(Warwick, 2015)]*

Again, the derived excellence improvements are reproduceable and reliable, as they stem from thorough literature research. Transferability to development projects with a lower or no involvement of the government is limited. They should be further described to increase authenticity of the given excellence improvements. This would also increase the applicability.

Table 2-6: Assessment of the excellence improvements as described by Reid & Rhodes

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Reid & Rhodes, 2016	●	●	◕	◑	◑

Systems Engineering Handbook – INCOSE, 2015

INCOSE's systems engineering handbook (Walden et al., 2015) is a standard work published by the international council on systems engineering (INCOSE). INCOSE unifies the systems engineering experience of various organizations and current research in systems engineering.

According to Walden et al. (2015, p.189), the benefits of a model-based approach over a traditional document-based approach to systems engineering are:

- *Improved communications among the development stakeholders (e.g., the customer, program management, systems engineers, hardware and software developers, testers, and specialty engineering disciplines)*
- *Increased ability to manage system complexity by enabling a system model to be viewed from multiple perspectives and to analyze the impact of changes*
- *Improved product quality by providing an unambiguous and precise model of the system that can be evaluated for consistency, correctness, and completeness*
- *Enhanced knowledge capture and reuse of the information by capturing information in more standardized ways and leveraging built-in abstraction mechanisms inherent in model-driven approaches. This in turn can result in reduced cycle time and lower maintenance costs to modify the design*
- *Improved ability to teach and learn SE [systems engineering] fundamentals by providing a clear and unambiguous representation of the concepts*
- *Information is captured in models and maintained throughout the life cycle*

As INCOSE represents a variety of industries and organizations, the transferability of the presented results is high. As there is ambiguity in the formulation of the results, the application is limited. To increase authenticity, the given improvements should be further described. Reproducibility and reliability can be increased by further describing how the benefits were obtained.

Table 2-7: Assessment of the excellence improvements as described by INCOSE

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
INCOSE, 2015	○	◔	◕	●	◑

Model-based systems engineering: Motivation, current status, and research opportunities – Madni & Sievers, 2018 and Economic Analysis of Model-Based Systems Engineering – Madni & Purohit, 2019

A pure research perspective on MBSE can be found in Madni and Sievers (2018) and Madni and Purohit (2019). While the first paper describes motivation, current practices, and research opportunities in MBSE, the later analyses the economics behind MBSE. With both papers giving an extract of excellence improvements, achievable through MBSE from a research perspective.

Madni and Sievers (2018, p.173) motivate MBSE through the following aspects:

- *Achieving effective communication among stakeholders, that is, the individuals and organizations involved in specifying, using, maintaining, deploying, designing, and testing the system.*
- *Model-based approaches are enabling the creation of system representations that are easy to use while also facilitating reuse of component models within the architecture.*
- *The strongly linked nature of the information in the models enables comprehensive traceability analyses by maintaining an audit trail of all information supplied, data generated, and decisions made.*
- *The use of declarative models with explicit interfaces can facilitate collaboration among individuals with expertise in different disciplines. Model gaps uncovered during collaboration can be jointly addressed by the engineering team.*
- *A collaborative system engineering team needs certain information in common to establish a shared context for discussion. [...] In large organizations, maintaining a shared context is especially important for meaningful collaboration. These concerns are addressed by MBSE.*

In 2019, Madni and Purohit (2019, p.4) add three more promises of model-based systems engineering:

- *Since dependencies across multiple disciplines are explicitly addressed in the model, a change made in one part of the model is automatically reflected in all the impacted parts of the model. This feature makes it possible to maintain consistent and up-to-date information in the integrated digital model.*
- *MBSE provides opportunities to capture and harmonize information from multiple disciplines within an integrated digital model of the system.*
- *Completeness, consistency, traceability and contradiction checks can be performed.*

Traceability and transparency of the presented results is limited, as there is a lack of justification. However, as the improvements are reasonable and authentic, traceability and transparency are partly achieved. The results incorporate and are transferable between different industries. Applicability of the improvements should be increased by recommending actions for particular industries.

Table 2-8: Assessment of the excellence improvements as described by Madni & Sievers and Madni & Purohit

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Madni & Sievers, 2018 Madni & Purohit, 2019	◑	◑	●	●	◕

A practical Guide to SysML – Friedenthal et al., 2015

Friedenthal et al. (2015) describe how to use the SysML to model systems and how to enable a model-based systems engineering approach. Friedenthal et al. (2015, p.20) list the following potential benefits of the transition from a document- to a model-based approach:

- *Enhanced communications*
  - *Shared understanding of the system across the development team and other stakeholders.*
  - *Ability to present and integrate views of the system from multiple perspectives.*
- *Reduced development risk*
  - *Ongoing requirements validation and design verification.*
  - *More accurate cost estimates to develop the system.*
- *Improved quality*
  - *More complete, unambiguous, and verifiable requirements.*
  - *More rigorous traceability between requirements, design, analysis, and testing.*
  - *Enhanced design integrity.*
- *Increased productivity*
  - *Faster and more comprehensive impact analysis of requirements and design changes.*
  - *More effective exploration of trade-space.*
  - *Reuse of existing models to support design evolution.*
  - *Reduced errors and time during integration and testing.*
  - *Automated document generation.*
- *Leveraging the models during downstream lifecycle phases*
  - *Support operator training on the use of the system.*
  - *Support diagnostics and maintenance of the system.*
- *Enhanced knowledge transfer*
  - *Efficient capture of domain knowledge about the system in a standardized form that can be accessed, queried, analyzed, evolved, and reused.*

Reproducibility and reliability of the enlisted benefits should be improved through describing how they were derived. The applicability of the potentials is generally given, examples and more details should be added. The benefits are highly transferable. Authenticity is given but should be increased through further differentiating categories like “increased productivity”.

Table 2-9: Assessment of the excellence improvements as described by Friedenthal et al.

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Friedenthal et al., 2015	◔	◔	◕	●	◑

Summary of the current state regarding MBSE excellence improvements

Table 2-10 summarizes the assessment of the current work towards excellence improvements through MBSE regarding five quality criteria.

Table 2-10: Summary of the assessment of excellence improvements regarding the five quality criteria

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Voirin et al., 2015	◑	◑	●	◑	●
Dean & Phillips, 2015	◑	◑	●	◔	●
Bone et al., 2018	●	●	◑	◑	◕
Reid & Rhodes, 2016	●	●	◕	◑	◑
INCOSE, 2015	○	◔	◕	●	◑
Madni & Sievers, 2018 Madni & Purohit, 2019	◑	◑	●	●	◕
Friedenthal et al., 2015	◔	◔	◕	●	◑

2.2.3 Success measure examination

First, it should be emphasized that success measures examined in this section are metrics that are influenced by the use of models, but not metrics measuring the quality of models or the modelling approach like in Giachetti (2017). The purpose of the metrics presented in this section are measuring the success of the MBSE transformation of the development environment. That means, that the metrics measure the achievement of the excellence improvements described in the previous section. It should also be noted, that if the success metrics are off, the model quality metrics can be an indicator for the adequacy with which the MBSE transformation has been implemented.

Success measures in the context of model-based systems engineering can be found in three publications. A brief description of the context of the publication is followed by a list of the mentioned measures. Each contribution is assessed regarding the fulfillment of the five quality standards for conclusions defined in subchapter 1.2: reproducibility, reliability, authenticity, transferability, and applicability.

A practical Guide to SysML – Friedenthal et al., 2015

Friedenthal et al. (2015) describe how to use the SysML to model systems and how to enable a model-based systems engineering approach. In this work, three kinds of metrics are presented: maturity metrics, MBSE deployment metrics, metrics measuring the MBSE benefits (Friedenthal et al., 2015, p.26). Some of the latter according to (Friedenthal et al., 2015, pp.27, 28, 544) are:

- *Reduction in time to assess a requirements or design change impact*
- *Reduction in the number of requirements changes or discrepancies that are identified during integration and test*
- *Quality of the design:*
  - *Extent to which the requirements are satisfied*
  - *Performance properties, such as response time, throughput, and accuracy*
  - *Physical properties, such as weight, size, and power; and other properties, such as reliability and cost*
- *Design partitioning, in terms of the level of cohesion* (extent to which a component can perform its functions without requiring access to external data) *and coupling* (number of interfaces between model elements) *of the design*
- *Progress of the design and development effort:*
  - *Extent to which the system design satisfies the system requirements*
  - *Number of use-case scenarios that have been completed*
  - *Percent of logical components that have been allocated to physical components*
  - *Extent to which components have been verified and integrated into the system*
- *Amount of reuse and modification of existing models versus creating new models*

Friedenthal et al. (2015, p.548) underline that the itemized improvement metrics should be monitored during the transformation to assess the effort. To do that, sizing parameters for scaling the improvements can be used (Friedenthal et al., 2015, p.28). Exemplary sizing parameters are model elements, requirements, system/component states and system/component interfaces.

Evaluating the enlisted metrics, it becomes clear that they are highly transferable. Applicability is limited, as some of the objectives are only stated on an abstract level. As there is no description of the way the metrics have been derived, reproducibility and reliability are improvable. A limited reliability is achieved through the high authenticity of the metrics.

Table 2-11: Assessment of the MBSE success metrics as described by Friedenthal et al.

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Friedenthal et al., 2015	◑	◑	◑	●	◑

Systems Engineering Leading Indicators Guide – Roedler & Rhodes, 2007

In their guide to systems engineering leading indicators, Roedler et al. (2007) give an overview of measures "*for evaluating the effectiveness of […] how a specific activity is applied on a program in a manner that provides information about impacts that are likely to affect the system performance objectives*" (Roedler et al., 2007, p.6). The specific activity in this case is systems engineering. The purpose of the leading indicators is described in the second chapter of the guide, subsequently the measurement of the leading indicators is further specified in specification sheets. Leading indicators are described for the following systems engineering aspects (Roedler et al., 2007, p.3):

- *Requirements,*
- *System definition change backlog,*
- *Interfaces,*
- *Requirements validation,*
- *Requirements verification,*
- *Work product approval,*
- *Review action closure,*
- *Technology maturity,*
- *Risk exposure,*
- *Risk handling,*
- *Systems engineering staffing and skills,*
- *Process compliance,*
- *Technical measurement*
- *Facility and equipment availability*
- *Defect and error*
- *System affordability*
- *Architecture*
- *Schedule and cost pressure*

The long list of contributors from various backgrounds secures the high reliability and authenticity of the enlisted metrics. The transferability of the leading indicators from systems engineering to model-based systems engineering is up for discussion. Also, the applicability of some of the trend-based measures is difficult, as they require a high measurement effort. General applicability is given through the detailed specification of the measurement. Through an introduction clarifying all open question and defining central concepts, reproducibility is fully achieved.

Table 2-12: Assessment of the MBSE success metrics as described by Roedler et al.

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Roedler & Rhodes, 2007	●	●	●	◑	◕

How Product Development Organizations can Achieve Long-Term Cost Savings Using Model-Based Systems Engineering (MBSE) – Krasner, 2015

In his white paper, Krasner (2015) compares key metrics of embedded system development projects using and not using MBSE. The data presented in this report is said to be statistically accurate as well as authentic and is based on a survey and a comparison tool (Krasner, 2015, p.2). To compare the system development projects, the following metrics have been used by Krasner (2015, p.6):

- *Development time months*
- *% Behind schedule*
- *Months behind*
- *% Cancelled*
- *Months lost to cancellation*
- *SW developers/project*
- *Average developer months/project*
- *Dev. months lost to schedule*
- *Dev. months lost to cancellation*
- *Total developer months/project*
- *At $10,000/developer month*
  - *Average developer cost/project*
  - *Average cost to delay*
  - *Average cost to cancellation+*
  - *Total developer cost/project*

Reproducibility and authenticity of the presented metrics is limited, as some of them are not clearly defined and a description of the measurement method is missing. Also, reliability of the results is critical, as there is no description of the survey participants demographics. The metrics, derived from practice, are fully applicable. The transferability of these metrics from embedded systems to other systems is questionable.

Table 2-13: Assessment of the MBSE success metrics as described by Krasner

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Krasner, 2015	◑	◔	◑	◑	●

Summary of the current state regarding MBSE success metrics

Table 2-14 summarizes the assessment of the presented contributions to MBSE success metrics regarding five quality criteria.

Table 2-14: Summary of the assessment of contributions to MBSE success metrics regarding five quality criteria

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Friedenthal et al., 2015	◑	◑	◑	●	◑
Roedler & Rhodes, 2007	●	●	●	◑	◕
Krasner, 2015	◑	◔	◑	◑	●

2.2.4 Environment structure and influence determination

The environment structure and elements that are influenced by an MBSE transformation are subject to or part of the following eight publications. A brief description of the context of the publication is followed by an overview of the environment structure and definition of its elements and relationships. Finally, each contribution is assessed regarding the fulfillment of the five quality standards for conclusions defined in subchapter 1.2. These are reproducibility, reliability, authenticity, transferability, and applicability.

Systems Engineering Guidebook – Martin, 1997 and Survey of Model-Based Systems Engineering (MBSE) Methodologies – Estefan, 2008

In his guidebook Martin (1997) makes an effort to describe the elements and relationships within a systems engineering development environment. Estefan (2007, p.1) builds on this description and defines an MBSE methodology for such an environment as *"a collection of related processes, methods, and tools used to support the discipline of systems engineering in a "model-based" or "model-driven" context"*. He visualizes this understanding of a methodology and what it contains as shown in Figure 2-2.

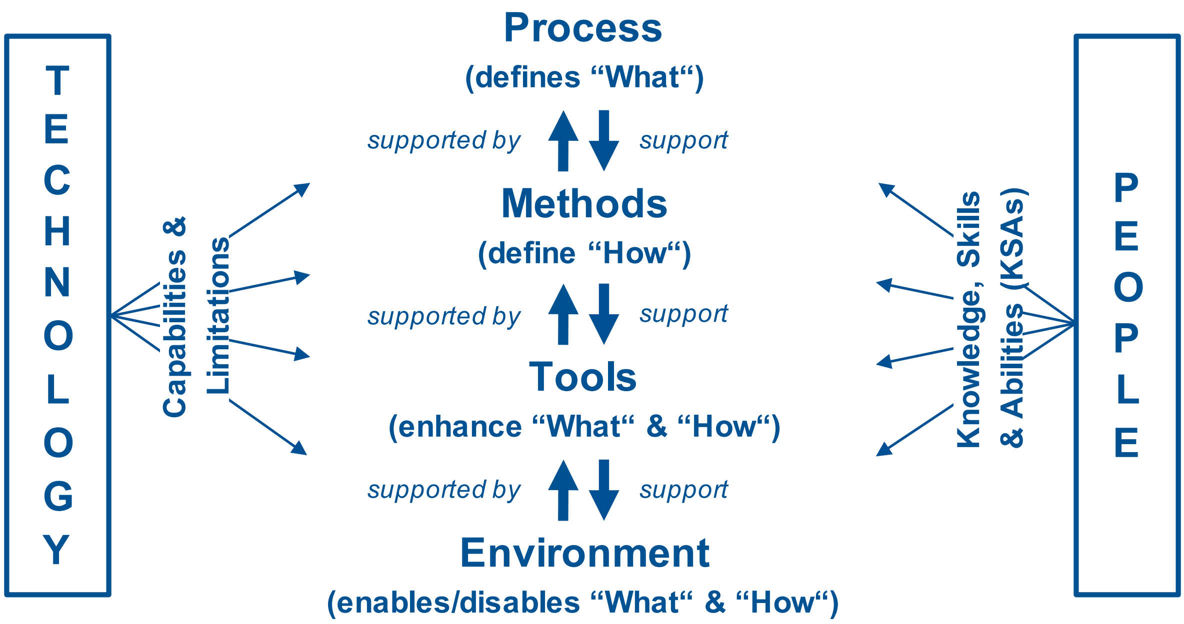

Figure 2-2: Elements of a methodology, as described by Martin (1997, pp.53, 67) and adopted from Estefan (2007, p.3)

Martin (1997, pp.54-57, 66, 67) further defines the elements of the methodology, referred to as PMTE elements, as:

- Process: *logical sequence of tasks performed to achieve a particular objective*; *defines "What" is to be done*
- Method: *techniques for performing a task*; *defines "How" each task is performed*
- Tool: *instrument that, when applied to a particular method, can enhance the efficiency of the task*; *in a broader sense, a tool enhances the "What" and the "How"*
- Environment: *consists of the surrounding conditions, which can be social, cultural, personal, physical, organizational, or functional*; *an environment enables or disables the "What" and the "How"*
- Technology: *capabilities and limitations of technology and their influence on the elements must be considered when developing an MBSE environment*; *they can either help or hinder the systems engineering efforts*
- People: *similarly, knowledge, skills and abilities of the people involved have to be considered*; *they often have to be enhanced through special training and assignments when new elements are introduced*

The relationships between the elements are simplified by Martin and Estefan in the figure given above. Actually, tools and the environment should have relations to the "what" and "how", not only to tool and/or method.

Evaluating the environment structure, authenticity is given. What could be seen as internal contradiction is that the boundaries between environment and technology as well as people are relatively vague and that the relationships are not fully visualized. Through its high-level of abstraction, the environment is well transferable to various organizational contexts. The target-oriented wording of the elements and their compact definition make the environment structure highly applicable. Again, a clearer definition of the differences between technology, people, and environment is room for improvement. As the author bases his results on general observations and common sense, reproducibility is fully given. These observations and the application of common sense could have been enhanced through the use of more sophisticated research methods to achieve further reliability of the environment structure.

Table 2-15: Assessment of the environment structure as described by Martin and Estefan

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Martin, 1997 & Estefan, 2008	●	◐	◐	●	◕

Seamless Model-Based Development: From Isolated Tools to Integrated Model Engineering Environments – Broy et al., 2010

Broy et al. (2010) depicts a model-based engineering environment for the development of embedded software-intensive systems. This paper has a strong emphasis on the integration of tools in seamless IT systems. Figure 2-3 shows the main ingredients to achieve a seamless model-based development. Only the engineering environment shown in the top row is relevant to this thesis, as it operationalizes all other layers and therefore represents the development environments in which the engineers work.

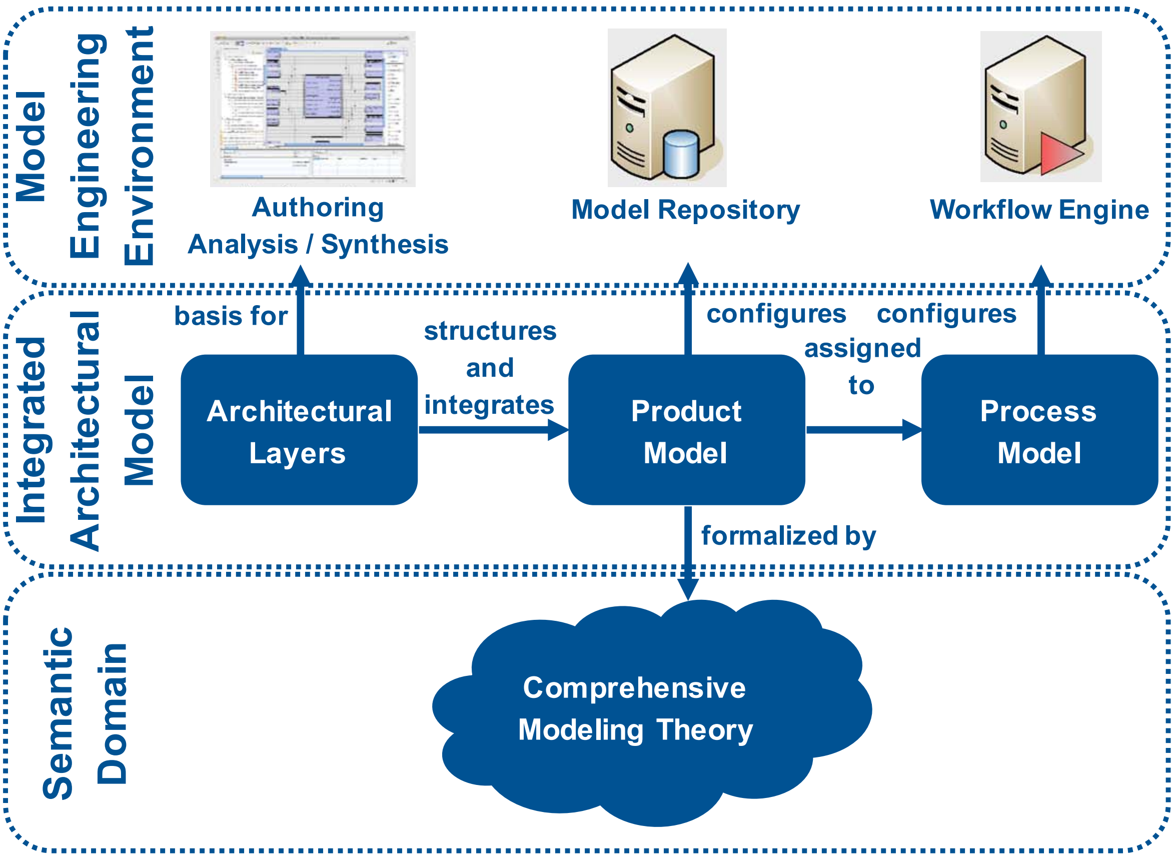

Figure 2-3: Main ingredients for a seamless model-based development, adopted from Broy et al. (2010, p.532)

The depicted engineering environment consist of the authoring analysis/synthesis, model repository, and workflow engine. According to Broy et al. (2010, p.533), the three ingredients are defined as follows. The authoring analysis/synthesis contains "*advanced tools for editing models that directly support their users to build up models and tools for analyzing the product model and synthesizing new artifacts out of the product model*". The model repository "*maintains the different artifacts including their dependencies*". Finally, the workflow engine "*guides the engineers trough the steps defined by the development process*".

The environment structure is described in a very scientific way, making an immediate application in practice difficult. It has been developed focusing on software-intensive embedded systems, leaving the transferability to other systems in question. However, for these systems, the authenticity and reliability are sufficiently secured, through multiple examples and a study of implementation obstacles. Reproducibility of results could be improved through structuring the paper in a way that underlines the general message.

Table 2-16: Assessment of the environment structure as described by Broy et al.

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Broy et al., 2010	◑	●	●	◑	◔

Overview of architecture frameworks and modeling languages for model-based systems engineering – Reichwein & Paredis, 2011

Reichwein and Paredis (2011) present an overview of architecture frameworks and modeling languages for model-based systems engineering, in order to familiarize system designers with the main concepts of MBSE. According to them, architecture framework and modeling languages represent the major elements of such a concept. They describe the capabilities of an architecture framework as defining the structure and content of architecture descriptions and incorporating best practices to establish such descriptions (Reichwein & Paredis, 2011, p.3). They further specify that architecture frameworks generally do not prescribe a specific notation. *"Notations for multiple system aspects which can span several views and play an integrative role by tying multiple views together"* are defined as modeling languages or architecture description languages (Reichwein & Paredis, 2011, p.5). They further embody concepts and rules to describe various system views.

Reichwein and Paredis focus on the architecture of systems, limiting the transferability of the derived elements to other system lifecycle phases. Reproducibility is fully achieved as they rigorously present the fundamentals of their work. Although listing a lot of examples for both elements, there is no example given on how to create a meaningful concept through selecting complementary examples. This reduces applicability and hinders the assessment of reliability. The presented structure of an MBSE concept generally makes sense as the identified elements are seen as the major commitments towards an MBSE approach.

Table 2-17: Assessment of the environment structure as described by Reichwein & Paredis

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Reichwein & Paredis, 2011	●	◑	◑	◔	◔

Model-based systems engineering: Motivation, current status, and research opportunities – Madni & Sievers, 2018

Madni and Sievers (2018) discuss motivation, current state and research opportunities in MBSE. They visualize the key high-level concepts and relationships in MBSE through Figure 2-4.

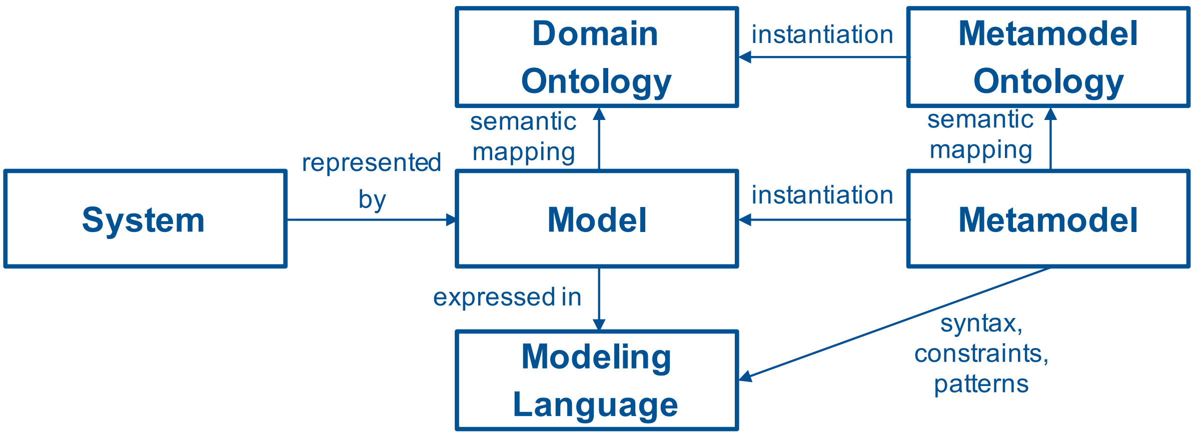

Figure 2-4: Key high-level concepts and relationships in MBSE adopted from Madni and Sievers (2018, p.177)

The high-level concepts are system, model, metamodel, metamodel and domain ontology as well as the modeling language. They are defined as follows (Madni & Sievers, 2018, p.177):

Ontology – *"formal explicit conceptualization of a problem domain shared by stakeholders; it presents a controlled vocabulary that comprises a set of agreed upon terms (semantic domain) and rules for using and interpreting them within the domain."*

Metamodel – *"define the abstract syntax of a modeling language used to express models in a domain of interest. Metamodels comprise object types, relationships between object types, attributes of object types, and the rules that enable combining object types and relationships."*

Modeling language, model, system, and domain are not further defined.

As Figure 2-4 shows, the model is instantiated through the Metamodel and represents the system. The model is expressed in a modeling language and its semantic is defined in the domain ontology. The metamodel predetermines the syntax, constraints, and patterns of the modeling language and the semantic mapping of the metamodel ontology, which instantiates the domain ontology.

The presented concepts and relationships are very abstract and represent only a small part of MBSE, namely the model and its backend. Therefore, the transferability of the presented environment in model-based environments is high regarding descriptive models, but the applicability is low. The form in which the relationships are described is not consistent, therefore authenticity is low. With the given definitions of the concepts, the relationships are reproducible. It is questionable if all the concepts are necessary to describe the context, leading to a mediocre reliability of the relationship diagram.

Table 2-18: Assessment of the environment structure as described by Madni & Sievers

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Madni & Sievers, 2018	◕	◑	◔	◕	◔

Combining Model-Based Systems Engineering, Simulation and Domain Engineering in the development of Industrial Automation Systems – Scheeren & Pereira, 2014

Scheeren and Pereira (2014) compare a document-based to a model-based approach in light of the development of an automation system. To build a model-based environment, they combine *tools and languages* with a *methodology and framework* in a model-based engineering approach (Scheeren & Pereira, 2014, pp.41-43). They validate the resulting model-based engineering approach in a case study and compare its performance to a document-based engineering approach.

The applicability, authenticity, and reliability of their approach is proven through the case study. The transferability of the approach is limited as there is no transferable middle ground between the high-level concepts and the detailed description of the approach. Also, the reproducibility could have been increased through a lengthy description of the design decisions leading to the environment used in the case study and further examination of the results of the comparison.

Table 2-19: Assessment of the environment structure as described by Scheeren & Pereira

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Scheeren & Pereira, 2014	◔	●	●	◔	●

SysML Distilled – Delligatti, 2014

In his brief guide to the systems modeling language Delligatti (2014, p.4) introduces the *“three pillars of MBSE”*. Namely, modeling language, modeling methods and modeling tools. He defines a modeling language as *“a semiformal language that defines the kinds of elements you're allowed to put into your model, the allowable relationships between them, and—in the case of a graphical modeling language—the set of notations you can use to display the elements and relationships on diagrams.”*. A modeling method according to Delligatti is *“a document set of design tasks that a modeling team performs to create a system model.”* It ensures consistence and purpose of the modeling work. Finally, modeling tools are described by Delligatti (2014, pp.5-7) as *“a special class of tools that are designed and implemented to comply with the rules of one or more modeling languages, enabling you to construct well-formed models in those languages.”*.

The three pillars are very authentic, as they describe general decision points in the MBSE adoption. The concept is reproducible through using an understandable wording. The completeness of the pillars is questionable, as other elements in the context of an MBSE environment are not described. Also, it is questionable if the language has to be itemized, as it is often included in the tool choice, leading to a mediocre reliability and applicability. The concept is transferable for descriptive models.

Table 2-20: Assessment of the environment structure as described by Delligatti

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Delligatti, 2014	●	◔	●	◕	◑

A Practical Guide to SysML – Friedenthal et al., 2015

In their book on SysML and MBSE, Friedenthal et al. (2015, p.21) state that "*transitioning to MBSE underscores the need for up-front investment in processes, methods, tools, and training*". By process, the *"baseline systems engineering process of the organization"* is understood and the systems engineering process is supported by methods. Training is specified as the development of *"skill level in the use of the language, method, and tools"* (Friedenthal et al., 2015, pp.545-546). Tools are categorized, but the term is not further explained.

All terms are understandable and close to the wording used in practice. Therefore, the concept is reproduceable and through making use of examples applicable. The reliability and transferability of the statement is limited, as there might be no investment necessary in some of the given elements. The described aspects of an MBSE transformation are fully authentic.

Table 2-21: Assessment of the environment structure as described by Friedenthal et al.

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Friedenthal et al., 2015	●	◔	●	◑	●

Systems Engineering - Rambo et al., 2017

Rambo and Weber (2017) give an overview of virtues, operations, and tools in systems engineering practices. They define the triad of modeling (Rambo & Weber, 2017, p.173), consisting of method, language, and tool. They emphasize that they have to fit together in order to work properly and give an exemplary instantiation of the triad.

All three elements are authentic and applicable. They are transferable in descriptive modeling. It is questionable if the language has to be itemized, as it is often included in the tool choice. This reduces the reliability of the concept. As there is no documentation of the way how these three elements have been derived, reproducibility is hard to achieve.

Table 2-22: Assessment of the environment structure as described by Rambo et al.

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Rambo et al., 2017	◔	◑	●	◕	●

Summary of the current state regarding MBSE environment structures

Table 2-23 summarizes the assessment of the presented environment structures and elements that are influenced by an MBSE transformation regarding five quality criteria.

Table 2-23: Summary of the assessment of environment structures presented in literature regarding five quality criteria

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Martin, 1997 & Estefan, 2008	●	◑	◑	●	◕
Broy et al., 2010	◑	●	●	◑	◔
Reichwein & Paredis, 2011	●	◑	◑	◔	◔
Madni & Sievers, 2018	◕	◑	◔	◕	◔
Scheeren & Pereira, 2014	◔	●	●	◔	●
Delligatti, 2014	●	◔	●	◕	◑
Friedenthal et al., 2015	●	◔	●	◑	●
Rambo et al., 2017	◔	◑	●	◕	●

2.2.5 Transformation approach exploration

Transformation approaches to adopt an MBSE methodology are a rare topic of publications. The following four publications contribute frameworks for or pitfalls in the MBSE adoption process. A brief description of the context of the publication is followed by an overview of the transformation approach. The fulfillment of the five quality standards for conclusions from subchapter 1.2, reproducibility, reliability, authenticity, transferability, and applicability, is assessed.

Recommendations for Introducing Model Based Systems Engineering – Selberg & Asberg, 2017

In their master's thesis, Selberg and Asberg (2017, p.5) created *"a framework which provides recommendations for how to introduce MBSE by finding and addressing areas of particular concern for system engineering companies"*. In order to do so, they conducted a literature review and interviews with eleven MBSE experts from Saab AB.

The framework consists of eight steps: purpose, prestudy, choose alternative, prototype, impact of solution, training, and test-project (Selberg & Asberg, 2017, p.71). Its distribution on a timeline as well as the responsible stakeholder are visualized in Figure 2-5.

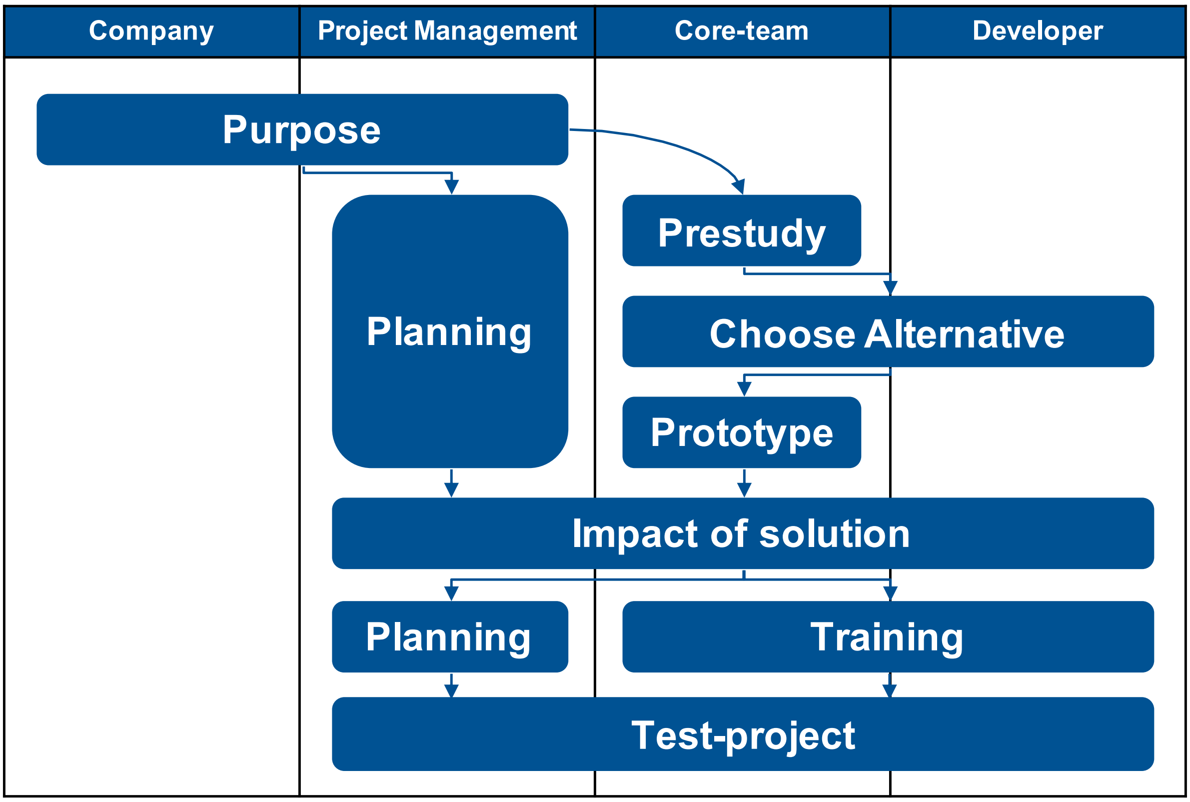

Figure 2-5: Framework for the introduction of MBSE adopted from Selberg and Asberg (2017, p.77)

Reliability and reproducibility of the framework is achieved through the detailed review of the conducted interviews and literature study. The authenticity could be improved by increasing the rigor in the naming of the steps. The applicability of the framework is high, but an example would facilitate the rollout. Transferability of the framework is limited, as it is derived from the experience of a single company and its industry.

Table 2-24: Assessment of the transformation approach as described by Selberg & Asberg

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Selberg & Asberg, 2017	●	●	◕	◔	◕

How to Fail at MBSE – Hause, 2013

In his presentation, Hause (2006), who is a consultant at the software development company atego (now PTC), enumerates 17 things organizations should not do when adopting MBSE. These are according to Hause (2006, p.13):

- *Avoid training and mentoring*
- *Discourage collaboration*
- *Avoid professional and standards organizations*
- *Adopt an external process wholesale*
- *Duplicate your work*

- *Avoid configuration management*
- *Stay ignorant of best practice*
- *Ignore metrics*
- *Conduct paper-based reviews*
- *Abuse lean and agile development*
- *Avoid optimizing your process*
- *Model too much, too early*
- *Delay building documentation and code templates*
- *Use incompatible modeling tools*
- *Adopt a custom notation*
- *Duplicate paper-based processes with tools*
- *Buy a tool first (any tool)*

The presented lurking pitfalls when adopting MBSE are highly authentic and applicable, as they are described in the imperative. Transferability of the pitfalls is not entirely given, as there is no evaluation which pitfalls might concern which industry the most. As there is no information about the approach leading to the identification of the presented pitfalls, they are not reproducible and there is limited reliability in them.

Table 2-25: Assessment of the transformation approach as described by Hause

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Hause, 2013	○	◑	●	◕	●

Modellbasierte System-Entwicklung mit SysML – Alt, 2012

Alt (2012) describes the introduction of model-based system development in his book. Therefore, he picks and details five *"soft factors"* influencing the introduction of MBSE (Alt, 2012, pp.161-166):

- *Change of the mindset*
- *Support by the management*
- *Fit roles with the right employees*
- *Training*
- *Continuous tool chain*
- *Practical experience is important*

The enlisted factors are all authentic and transferable. The generic formulation of the factors makes it hard to recognize their appearance and thereby apply the given recommendations in practice. The reliability and reproducibility should be improved through explaining the context that these factors are derived from and further elaborate on the relevance of the factors.

Table 2-26: Assessment of the transformation approach as described by Alt

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Alt, 2012	◑	◑	●	●	◔

A practical Guide to SysML – Friedenthal et al., 2015

Friedenthal et al. (2015) describe how to use the Systems Modeling Language (SysML) to model systems and how to enable a model-based systems engineering approach. They outline how an improvement process to deploy SysML in an organization should look like. Figure 2-6 shows the five-phased improvement process for deploying SysML. The phases are further described in the book.

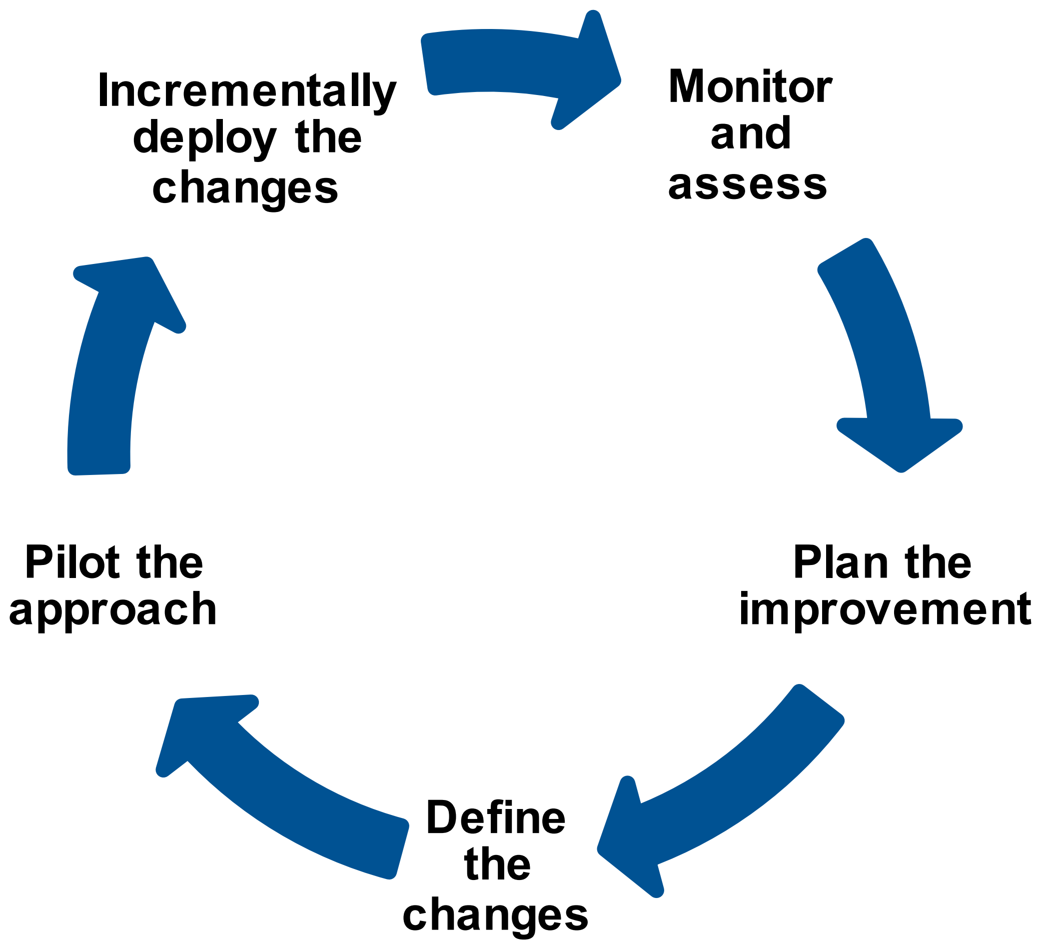

Figure 2-6: Improvement process for deploying SysML adopted from Friedenthal et al. (2015, p.557)

The presented process is derived with care and makes sense; therefore, it is highly authentic and reliable. Reproducibility should be improved by stating how the process was created. The transferability of the process to modeling languages other than SysML is to be discussed. However, the generic formulation is facilitating transfers. The applicability of the process is given but could be increased through an example.

Table 2-27: Assessment of the transformation approach as described by Friedenthal et al.

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Friedenthal et al., 2015	◕	●	●	●	◕

Summary of the current state regarding MBSE transformation approaches

Table 2-28 summarizes the assessment of the presented transformation approaches regarding five quality criteria.

Table 2-28: Summary of the assessment of transformation approaches regarding five quality criteria

Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Selberg & Asberg, 2017	●	●	◕	◔	◕
Hause, 2013	○	◑	●	◕	●
Alt, 2012	◑	◑	●	●	◔
Friedenthal et al., 2015	◕	●	●	●	◕

2.3 Directions from the state of the art

Coming from the assessment of the existing work regarding the quality criteria in the previous subchapter, visualized in Table 2-29, this subchapter draws conclusions to guide and sharpen the contribution provided to the research objectives through this thesis.

Table 2-29: Summary of the assessment of existing work regarding five quality criteria

MBSE potential estimation					
Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Madni & Purohit, 2019	◕	◑	●	●	◑
Excellence improvement identification					
Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Voirin et al., 2015	◑	◑	●	◑	●
Dean & Phillips, 2015	◑	◑	●	◔	●
Bone et al., 2018	●	●	◑	◑	◕
Reid & Rhodes, 2016	●	●	◕	◑	◑
INCOSE, 2015	○	◔	◕	●	◑
Madni & Sievers, 2018 Madni & Purohit, 2019	◑	◑	●	●	◕
Friedenthal et al., 2015	◔	◔	◕	●	◑
Success measure examination					
Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Friedenthal et al., 2015	◑	◑	◑	●	◑
Roedler & Rhodes, 2007	●	●	●	◑	◕
Krasner, 2015	◑	◔	◑	◑	●
Environment structure and influence determination					
Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Martin, 1997 & Estefan, 2008	●	◑	◑	●	◕
Broy et al., 2010	◑	●	●	◑	◔
Reichwein & Paredis, 2011	●	◑	◑	◔	◔
Madni & Sievers, 2018	◕	◑	◔	◕	◔
Scheeren & Pereira, 2014	◔	●	●	◔	●
Delligatti, 2014	●	◔	●	◕	◑
Friedenthal et al., 2015	●	◔	●	◑	●
Rambo et al., 2017	◔	◑	●	◕	●
Transformation approach exploration					
Author	Reproducibility	Reliability	Authenticity	Transferability	Application
Selberg & Asberg, 2017	●	●	◕	◔	◕
Hause, 2013	○	◑	●	◕	●
Alt, 2012	◑	◑	●	●	◔
Friedenthal et al., 2015	◕	●	●	●	◕

MBSE potential estimation

First of all, there is little literature about the initial assessment of the value or potential of MBSE. An authentic and transferable approach is conducted by Madni and Purohit (2019), categorizing industries according to lifespan, environment and system complexity. This is an interesting approach, that should be further developed regarding reproducibility, reliability, and applicability.

First, reproducibility and reliability should be addressed by **specifying which factors should be considered for categorization and why** these resemble the potential or value accessible.

Second, the organizations within the industries are heterogenous and the target audience for potential estimation heuristics are managers or chief systems engineers of these respective organizations. Therefore, an **estimation of the potential** should be possible **on an organizational level**, requiring a breakdown of categorization characteristics on this level.

Excellence improvement identification

The excellence improvements achievable through MBSE are well covered in literature. Four industrial case studies, a standard work as well as two scientific works, list numerous but similar benefits. All sources were predominantly authentic. The strength of the industrial case studies lies in their reproducibility, reliability, and applicability, whereas the strength of the scientific and standard works lies in the excellent transferability.

In order to **combine** the best of both worlds, the **excellence improvements observed in industrial case studies** should be combined **with the ones listed in scientific and standard works**. Thereby, universal MBSE capabilities fulfilling all quality characteristics should emerge.

Success measure examination

Three very different works were analyzed regarding measures indicating MBSE success. First, Friedenthal et al. (2015) make a good point why metrics are necessary and that they should be measured throughout the deployment of MBSE. But then it comes to specifying the enlisted metrics, a lot of questions like why this metric and how can it be measured effectively stay unanswered. Second, Roedler et al. (2007) do an excellent job deriving reliable, authentic, and reproducible leading indicators for systems engineering success. To date they do not incorporate the measurement of benefits achieved through an increased model-based workflow. Finally, Krasner (2015) uses traditional project metrics to measure the influence of MBSE. This works in retrospect comparison to justify MBSE but there are too many influencing factors to deduce success during MBSE deployment.

To deal with the shortcomings in current approaches, the metrics should be **linked to systems engineering as well as model-based objectives**, so that their purpose and intend is clear.

Secondly, the efficient **measurement** of the metrics should be **described as accurate as possible without sacrificing transferability**.

And lastly, in order to support the successful deployment of MBSE in an organization, they should be **significant** regarding the **indication of MBSE effects**.

Environment structure and influence determination

All works reviewed regarding a contribution toward a development environment structure covering the elements and relationships influenced by MBSE, cover different views on the development environment with distributed strengths and weaknesses. Covered viewpoints are methodology, information technology (IT) systems, modeling, and MBSE deployment.

In order to find a unified environment structure, all **views** with their respective elements and relationships **should be merged**. Emphasis should be on the equal coverage of all viewpoints, without overcomplicating the development environment, so that it still is applicable in practice.

As most environments stem from theoretical studies, the merged environment should be discussed with practitioners to **ensure applicability and authenticity**.

Transformation approach exploration

Literature on transformation approaches is versatile. While Selberg and Asberg (2017) present a company-specific framework, Hause (2006) lists applicable pitfalls, Alt (2012) lists soft influencing factors and Friedenthal et al. (2015) presents an excellent framework, lacking minor contributions towards reproducibility and applicability.

These minor contributions should be a **reproducible explanation on the creation and application of the framework** and exercising a **demonstrative example** to proof and facilitate the applicability of the framework.

The elaborated directions from the state of the art are addressed in the next chapter, which describes the creation of the guideline for the implementation of MBSE in product development.

3 Guideline design

This chapter acts on the identified directions from the state of the art by designing a guideline for the implementation of MBSE in existing product development environments. Therefore, literature studies, a survey, and expert interviews were conducted.

3.1 Overview

Figure 3-1 gives an overview of the resulting guideline and allocates the shaping contributions by literature, the survey, and expert interviews to the aspects of the guideline.

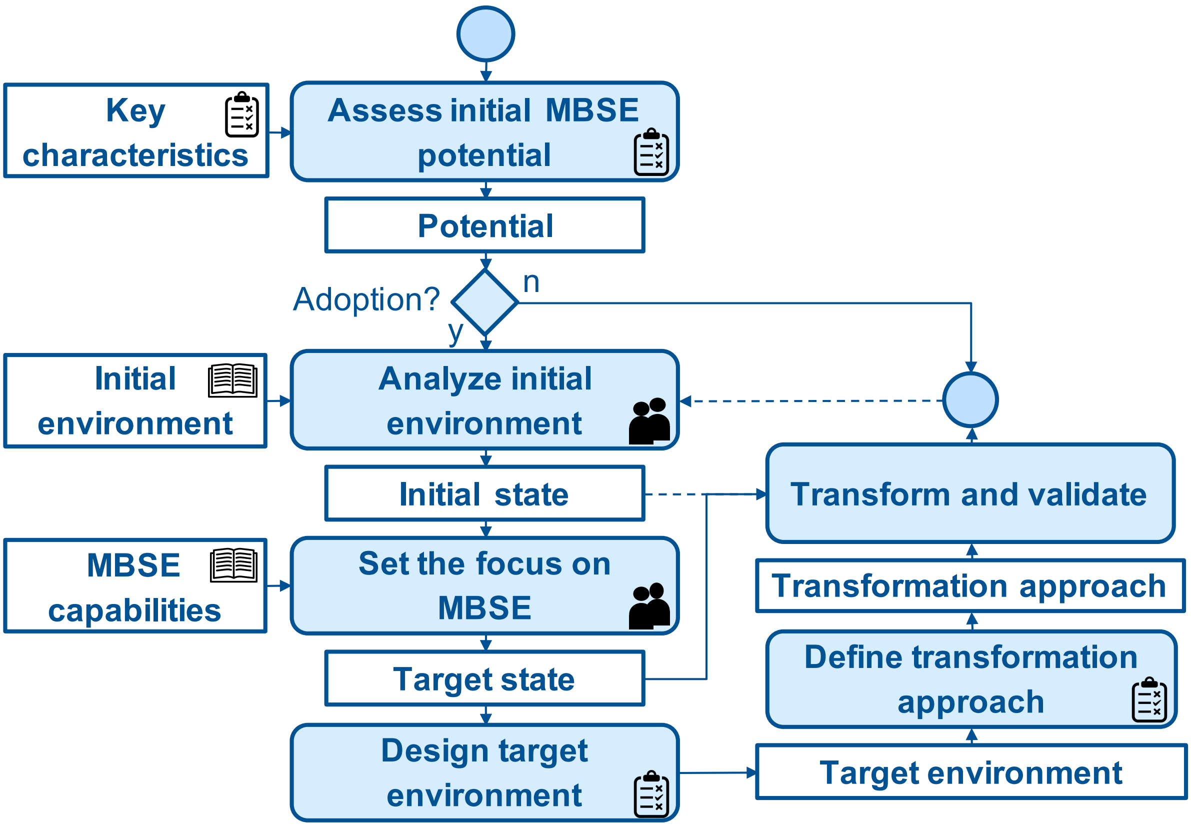

Figure 3-1: Overview of the guideline and contributions towards its design

The contributions covered in the following subchapter from literature focus on the structure of a development environment and the capabilities of MBSE. Another minor contribution will be made to the initial MBSE potential assessment.

The analysis of the survey results contributes mainly to the assessment of initial MBSE potential through using key characteristics, the design of a target environment and the definition of a transformation approach. On top of that, the state of practice regarding MBSE and associated issues will be depicted.

Finally, expert interviews will provide insights shaping the analysis of the initial environment and the selection of a focus on MBSE. Furthermore, the expert interviews validate aspects deduced from literature and the survey.

The detailed description of the contributions starts in the next subchapter with the literature studies, followed by the analyses of the survey and the insights from expert interviews.

3.2 Literature studies

Literature studies have been used to contribute to three research objectives. The first objective, to find a way of initially estimating the MBSE potential, is pursued by studying the initial reasons justifying the adoption of MBSE in section 3.2.1. The second research objective of identifying and generalizing the excellence improvements possible through MBSE is advanced in subsection 3.2.2 through examining the excellence improvements identified in the literature review (section 2.2.2) to derive general MBSE capabilities. Finally, a contribution to the fourth research objective, determining the development environment structure influenced by MBSE, is made. Using the environments depicted and assessed in section 2.2.4, the general elements and relationships within a development environment are deduced in subsection 3.2.3.

3.2.1 MBSE potential

According to Madni and Purohit (2019, p.1), *"several aerospace, automotive, and defense organizations have already begun or are contemplating the transition to model-based systems engineering (MBSE)"* to face an *"ever-increasing complexity of systems and system development programs"*. The same reason for the adoption of MBSE can be found in Scheeren and Pereira (2014, p.40), who state that efforts to develop MBSE tools and methods have been driven by increasing complexity, making the design of Industrial Automation Systems more challenging. Reichwein and Paredis (2011, p.1) recalls that *"systems engineering emerged as a discipline in order to address problems related to the design of complex systems"*. Friedenthal et al. (2015, p.XVII) highlight that *"the continuing increase in system complexity demands more rigorous and formalized systems engineering practices. In response to this demand […] the practice of systems engineering is undergoing a fundamental transition from a document-based approach to a model-based approach"*.

These exemplary quotes underline that there is a **unified understanding in the model-based systems engineering community, that complexity drives the adoption of MBSE**. Therefore, it can be assumed that the improvement potential, which can be achieved through implementing MBSE in an organization, is proportional to the prevailing complexity of that environment.

The next section will examine in detail, what capabilities MBSE offers to lift the improvement potential that we just discussed.

3.2.2 MBSE capabilities

As MBSE is a fairly young discipline (Reichwein & Paredis, 2011, p.1), there is no general specification of its capabilities. Research and industrial practice are still in a phase of postulating and exploring relevant capabilities. In the following section six shared MBSE capabilities are derived from the excellence improvements mentioned in four industrial case studies, a standard work as well as two scientific works, which were analyzed in section 2.2.2. The shared capabilities are dedicated to form a basis for the evaluation and selection of an appropriate focus on MBSE, as further explained in subchapter 4.3. Table 3-1 shows an overview of the excellence improvements derived from literature and the deduced six shared MBSE capabilities. In the following section each MBSE capability is described in detail.

Table 3-1: Overview of excellence improvements and the six derived MBSE capabilities

	Voirin et al. Thales Aerospace	**Dean & Phillips Lockheed Martin Space Systems**	**Bone et al. Department of Defense**	**Reid & Rhodes Department of Defense**	**INCOSE**	**Madni et al.**	**Friedenthal et al.**
Facilitate communication		Increase rigor in communication	Improve communication		Improve communication and reduce ambiguity	Improve communication and up-to-date information	
Improve collaboration	Increase continuity and joint decision making		Improve collaboration among specialists			Facilitate collaboration and harmonize information	Shared understanding
Enable reuse	Improve integration, reuse and product policy	Enable reuse		Increase reuse	Enhance information reuse	Facilitate reuse	Reuse of existing models to support design evolution
Improve transparency and traceability	Detect design flaws early	Check design against specification	Understand decision impact early	Cycle design concepts rapid and cheap	Evaluate consistency, correctness and completeness	Enable traceability analyses and other checks	Improved quality
Support the full lifecycle		Persist system details throughout the lifecycle			Maintain Information throughout the lifecycle		Leveraging the models during downstream lifecycle phases
Foster holistic problem understanding	Analyze customer needs in-depth		Assess project status and risk	Improve comprehension of complicated systems	Enable multiple perspectives		

Facilitate communication

A survey among German engineers revealed, that 40 % of development engineers spend more than 20 % of their time communicating and coordinating. Closely linked to this, is the amount of time spend acquiring information, which is more than 10 % of their time for 63 % of engineers (Müller et al. (2013) in Kissel (2014, p.3)).

MBSE improves the communication among the development stakeholders (Walden et al., 2015, p.189) by achieving effective communication among *"individuals and organizations involved in specifying, using, maintaining, deploying, designing, and testing the system"* (Madni & Sievers, 2018, p.173). In a model-based development environment, this is enabled through a **single source of information** for all disciplines. This could for example be an ontology-based information model *"to translate and extract useful information among a variety of models and model types"* (Bone et al., 2018, p.2). As models are fully interconnected and integrated in a single source of information, changes in one model are reflected in all impacted parts of the model. Therefore, the single source of truth always reflects the **latest information** and remains consistent (Madni & Purohit, 2019, p.4).

Missing rigor in communication is often an issue in development. The use of models and systems engineering practices leads to a *"clear and unambiguous representation of concepts"* (Walden et al., 2015, p.189). At Lockheed Martin model-based techniques were *"**increasing the amount of rigor** in the artifacts used for communicating behavior, relationships and interfaces to the software implementation team"* (Dean & Phillips, 2015, p.2).

In summary, MBSE facilitates communication among stakeholders through providing a single, up-to-date, and rigorous source of information.

Improve collaboration

Closely linked to the facilitation of communication is the improvement of collaboration respectively interdisciplinary engineering. Both, **horizontal** (different lifecycle phases) as well as **vertical collaboration** (different system levels) are fostered through MBSE. Bone et al. (2018, p.2) describe the improved communication among different specialists and stakeholders. And Voirin et al. (2015, p.2) highlights the *"increasing continuity and consistency between different engineering levels (e.g. system, sub-system […])"*.

Madni and Sievers (2018, p.173) describe that the improved collaboration is achieved through the use of *"declarative models with explicit interfaces"* integrated in a digital system model (Madni & Purohit, 2019, p.4), that *"captures and harmonizes information from multiple disciplines"*. This harmonization can be described as **shared system understanding** (Friedenthal et al., 2015, p.20), which is achieved through using systems engineering techniques. The shared system understanding leads to a shared and easily maintained *"context for discussion"*, which conversely leads to the uncovering of *"model gaps"* in a collaborative workflow (Madni & Sievers, 2018, p.173). These gaps can be addressed by the interdisciplinary engineering team through *"consistent, joint decision making"* (Voirin et al., 2015, p.2).

In brief, the horizontal and vertical collaboration, respectively interdisciplinary work, is improved through establishing a shared system understanding.

Enable reuse

A central aspect for the application of MBSE in most use cases is the reuse of architecture and engineering work results. The MBSE methodology is *"emphasizing the role of architecture, improving engineering and system integration efficiency"* (Voirin et al., 2015, p.2).

The amount of knowledge captured in models is enhanced and the reuse of information is increased, through more **standardized ways of documenting** this information and leveraging abstraction mechanisms built-in model-driven approaches (Walden et al., 2015, p.189). The so created and documented system representations facilitate the *"reuse of component models within the architecture"* (Madni & Sievers, 2018, p.173). Leading to an increased capitalization of definition and design results (e.g. justifications) (Voirin et al., 2015, p.2).

Reid and Rhodes (2016, p.3) distinguish the "*reuse of technical data and models from one project to another, as well as from one stage of a project to another"* Friedenthal et al. (2015, p.20) emphasize the reuse of models themselves, which is easier than reusing documents. At Lockheed Martin, model-based engineering, specifically the *"**clearly elucidated**"* **artifacts**, enabled not only their reuse but also increased the flexibility in their realization (Dean & Phillips, 2015, p.2). Realization being the implementation of the design, in the outlined case it is the flexible selection of the programming language.

Concluding, MBSE enables the reuse of architecture and engineering work results by documenting previous solutions in a more standardized way and leveraging the increased knowledge captured in models.

Improve transparency and traceability

There are two ways in which MBSE improves risk assessment, safety considerations, and quality assurance.

The first is to detect design flaws as early as possible (rather in design than in integration) (Voirin et al., 2015, p.2). This is achieved through evaluating consistency, correctness, and completeness through using traceability analyses within the **dependencies of the model** and in the audit trail of the model, covering *"all information supplied, data generated, and decisions made"* (Madni & Purohit, 2019, p.4; Madni & Sievers, 2018, p.173; Walden et al., 2015, p.189). Friedenthal et al. (2015, p.20) also emphasize the *"more rigorous traceability between requirements, design, analysis, and testing"*.

The second is to **cycle** design **concepts rapid and cheap** to understand the impact of requirement and design decisions early (Reid & Rhodes, 2016, p.3). Thereby, *"identify[ing] adverse consequences of the design"* before a specific design is chosen (Bone et al., 2018, p.2).

At Lockheed Martin, the design has been *"checked against the desired behaviors specified by the customer"* by using the *"execution capabilities of certain model-based tools"*, resulting in reduced defects (Dean & Phillips, 2015, p.2).

Summarizing, the dependencies of a model and its context as well as the opportunity to rapidly cycle design concept models are used to improve the transparency and traceability.

Support the full lifecycle

As all relevant information of the system are stored in a model when using an MBSE approach, information is **easily maintained** throughout the life cycle (Walden et al., 2015, p.189). Enabling the usage of this information in later lifecycle phases.

At Lockheed Martin, *"details about the system more easily persisted through the lifecycle and even eliminated duplication and divergence"* (Dean & Phillips, 2015, p.2). Streamlining later lifecycle activities like maintenance work or product recalls/updates or *"support[ing the] operator training on the use of the system"* (Friedenthal et al., 2015, p.20).

It can be concluded that easily accessible and maintained information provided by model-based engineering support later lifecycle activities.

Foster holistic problem understanding

MBSE methods focus not only on the design of the system, but also on the management of the system in other phases (INCOSE, 2007, p.15). Therefore, the application of MBSE fosters the creation of a holistic problem understanding.

The system model is a **multi-perspective** model, that can be viewed from a variety of viewpoints (Walden et al., 2015, p.189). Resulting in a holistic understanding of the problem or later solution (the system). An example for such a holistic viewpoint is the government interested in the status and risk of one of its acquisition projects (Bone et al., 2018, p.2). Another example is the creation of an in-depth understanding of the customer needs and how the system would fit its expectations is improved (Voirin et al., 2015, p.2). And the last example is that model-based methods offer a better analysis and comprehension of the complicated system, itself (Reid & Rhodes, 2016, p.3).

In conclusion, MBSE methods foster a holistic problem understanding, by creating in-depth knowledge about the system and its application from multiple perspectives.

Summarizing this section, the six MBSE capabilities are:

- **Facilitate communication** by providing a single, up-to-date and rigorous source of information
- **Improve** horizontal and vertical **collaboration** by establishing a shared system understanding
- **Enable** the **reuse** of architecture and engineering work results by documenting in a more standardized way and leveraging the increased knowledge captured in models
- **Improve transparency and traceability** by using dependencies of a model and its context as well as the opportunity to rapidly cycle design concept
- **Support the full lifecycle** by providing easily accessible and maintained information
- **Foster a holistic problem understanding** by creating in-depth knowledge about the system from multiple perspectives

After the MBSE capabilities have been derived from the excellence improvements in this section, the next section will identify the generic elements and relationships of a model-based development environment from the environments discussed in the literature review.

3.2.3 Model-based development environment

Section 2.2.4 describes and assesses the current state of research regarding model-based development environments. This section uses the current state as a baseline to identify the generic elements of and relationships within an MBSE environment.

Elements

Table 3-2 gives an overview of the model-based development environment elements derived from the provided sources and presents the five identified, generic elements on the right. Each of the elements is further described in this section.

Table 3-2: Overview of elements in a development environment as they are mentioned in MBSE literature and the five identified generic elements

Martin & Estefan	Broy	Reichwein	Madni	Sheeren	Delligatti	Friedenthal	Rambo & Weber	
Process	Workflow engine	Architecture framework	Model	Tools & languages	Modeling language	Process	Methodology	Process
Methods	Model repository	Modeling language	Modeling language	Methodology & framework	Modeling methods	Methods	Modeling language	Workflow/ Methods
Tools	Authoring analysis/ synthesis		Metamodel		Modeling tools	Tools	Modeling tool	Humans
Environment			Ontology			Training		Tools & IT
Technology								Models
People								

Process

A process, for this thesis, is defined as a *"logical sequence of tasks performed to achieve a particular objective"*, as in Martin (1997, p.54). It defines what is to be done in an abstract form and consists of tasks or process steps and milestones in which the achievement of a particular objective is assessed. Most organizations have a baseline systems engineering or product development process of this form in place, as implied by Friedenthal et al. (2015, p.545). Examples for such a process can be found in Rebentisch et al. (2017, p.265).

In government funded programs, the process can be referred to as an architecture framework or methodology like the Department of Defense Architecture Framework (DODAF) (U.S. Department of Defense, 2019), *"defining the structure and content of architecture descriptions and incorporating best practices to establish such descriptions"* (Reichwein & Paredis, 2011, p.3).

Workflow/Methods

Methods are *"techniques for performing a task"* and *"define 'How'"* each task is performed (Martin, 1997, p.55). They support the process (Friedenthal et al., 2015, p.545) and in combination form a workflow. The workflow can be seen as a process step, therefore in practice there is no sharp distinction between a workflow and a process. In theory, they are distinguished by their abstraction level and the workflow focusing on defining the "How" (Implementation), while the process focuses on defining the "What" (Objective).

Broy et al. (2010, p.533) makes this distinction tangible by stating that the *"workflow engine [...] guide[s] the engineers trough the steps defined by the development process"*. A workflow engine represents a rigorous presetting of methods and their combination.

Especially in early development, the engineer is rather free in choosing an adequate method and workflow. Using a common method e.g. in modeling *"ensures consistency and purpose of the modeling work"* (Delligatti, 2014, p.6).

Humans

The human is a key part of development environments. Two major forms of human instantiation in the development environment have to be considered. The individual and the organization.

The individual has three attributes influencing his performance in the model-based development environment: *"knowledge, skills and abilities"*. All three have to be considered and *"enhanced through special training and assignments"* (Martin, 1997, p.67) when new elements like MBSE are introduced. Friedenthal et al. (2015, p.546). further specify training as *"the development of skill level in the use of the language, method and tools"*, leaving out the influence on knowledge and abilities.

The organization creates the context in which the development environment is embedded. The major influences toward the environment are organizational culture and structure. They can enable or disable elements and relationships of the environment (Martin, 1997, p.54).

Tools & IT

A tool is an *"instrument that, when applied to a particular method, can enhance the efficiency of the task"* (Martin, 1997, p.56). As today most tools are digital and rely heavily on technology, *"capabilities and limitations of technology and their influence on the elements must be considered when developing the SEDE [systems engineering development environment]"* (Martin, 1997, p.66).

In a model-based development environment, Tools and IT is a key element. There is a need for *"advanced tools for editing models that directly support their users to build up models, [...] [and] tools for analyzing the product model and synthesizing new artifacts out of the product model [...]"*. Also, for model administration and curation a model repository that "*maintains the different artifacts including their dependencies"* (Broy et al., 2010, p.533) has to be created using a suitable technology.

Delligatti (2014, p.7) specifically defines modeling tools as *"a special class of tools that are designed and implemented to comply with the rules of one or more modeling languages, enabling you to construct well-formed models in those languages"*.

Models

Regarding models, which are defined in section 2.1.2, three additional terms found in the literature have to be defined here.

A model instantiates a metamodel within an ontology, using a modeling language.

The most general concept, an ontology, is a *"formal explicit conceptualization of a problem domain shared by stakeholders; it presents a controlled vocabulary that comprises a set of agreed upon terms (semantic domain) and rules for using and interpreting them within the domain"* (Madni & Sievers, 2018, p.6). It can be seen as overall concepts which are agreed upon and shared between the stakeholders, leading to a common understanding of a matter.

Reichwein and Paredis (2011, p.5) define modeling languages as *"notations for multiple system aspects which can span several views and play an integrative role by tying multiple* *views together"*. Delligatti (2014, p.5) further specifies that the modeling language sets the rules for modeling and predetermines graphical elements for displaying diagrams of the model.

According to Madni and Sievers (2018, p.6), metamodels *"define the abstract syntax of a modeling language used to express models in a domain of interest. Metamodels comprise object types, relationships between object types, attributes of object types, and the rules that enable combining object types and relationships"*.

Metamodel and modeling language are highly interlinked. The difference between them is, that the modeling language defines the notation and syntax, whereas the metamodel defines which relationships and objects can be used. Therefore, the metamodel is derived from the ontology to represent the agreed upon concepts and vocabulary, whereas the modeling language is independent from the ontology.

Figure 3-2 shows all identified elements of a model-based development environment.

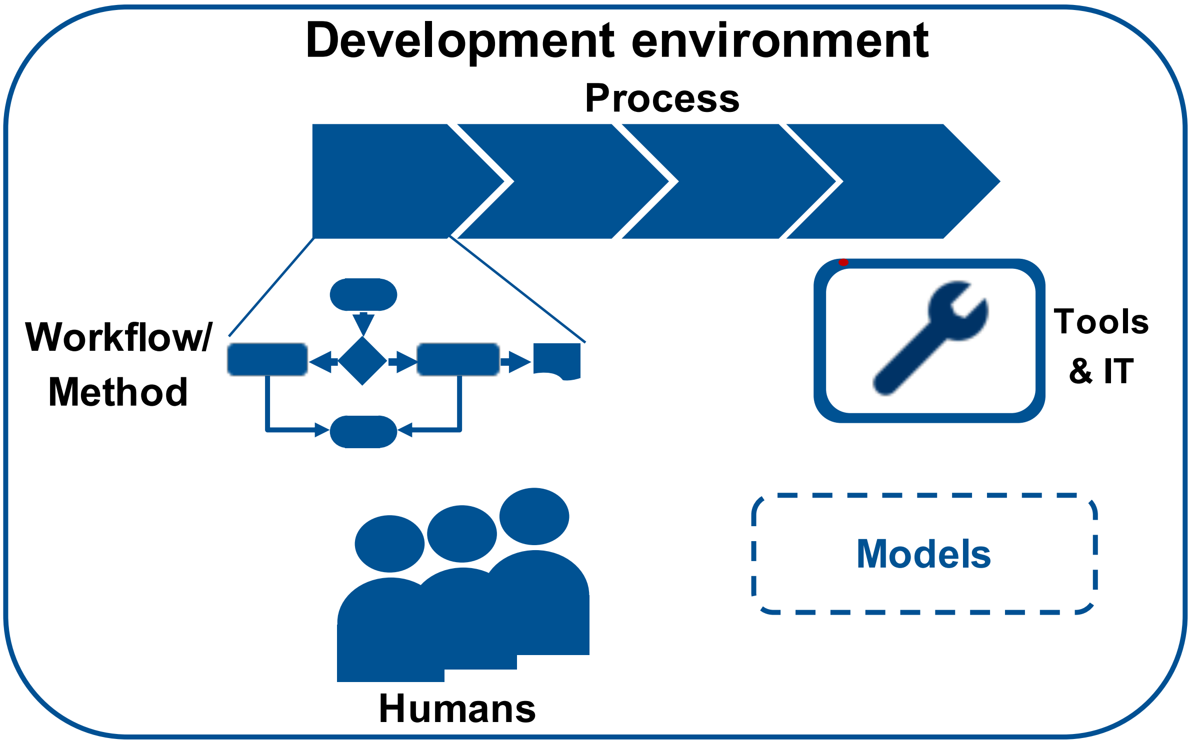

Figure 3-2: Identified elements of a model-based development environment

Relationships

After the elements of a development environment have been identified, it is now time to focus on the relationships between these elements. This section describes each relationship using contributions from literature and general observations. First, the **unilateral relationships** are outlined before the **reciprocative relationships** are specified.

Unilateral relationships

A tool is defined by Martin (1997, p.57) as an *"instrument that, when applied to a particular* *method, can enhance the efficiency of the task"*. This underlines that **tools & IT facilitate** the **workflow** and **methods.** The most common example are tools like Microsoft's Excel, offering a feature to program macros, automating and thereby facilitating methods or even whole workflows.

Models are the input and/or output of and are transformed within the Workflow/Method. It can be stated, that the **workflow** and **methods process models.** An example for such a processing is given by Broy et al. (2010, p.533), which state that models are used for analyses and synthesis.

A **model represents** a **system**. This relationship can be found in the environment depicted by Madni and Sievers (2018, p.177). The system can be represented from different viewpoints in various views. For example, the system "product" can be seen from a product management point of view in a cost structure view and a component structure view.

Finally, the **process** is **supported by** the **workflow** and the **method** (Friedenthal et al., 2015, p.545). They are deeply connected but can be distinguished by their abstraction level and the workflow focusing on defining the "How" (Implementation), while the process focuses on defining the "What" (Objective) (Martin, 1997, pp.53-56).

Reciprocative relationships

As Broy et al. (2010, p.533) describe, *"advanced tools for editing models [...] directly support their users to build up models, [...] [and] tools for analyzing the product model and synthesizing new artifacts out of the product model [...]"*. Exemplary are MBSE tools, which use consistency checks to secure high-quality work by the human building models. This example implies the reversed relationship of **humans operating** the **tools**. Often tools require training to develop skill level in their operation (Friedenthal et al., 2015, p.546).

Workflow and methods guide engineers through the steps defined by the process (Broy et al., 2010, p.533). Therefore, the **workflow** or **method coordinate** the work of the **humans**. They for example allocate the necessary tasks to the right professional. Thereby defining clear responsibilities. **Humans** then **execute** the **workflow** or **method** they are responsible for. This is also implied in the definition of a modeling method by (Delligatti, 2014, p.6), stating that a modeling method is *"a document set of design tasks that a modeling team performs to create a system model"*.

The statement by Broy et al. (2010, p.533) that the *"model repository maintains the different artifacts including their dependencies"*, shows that **tools** and especially the **IT** system **administer models**. Also, it reflects, that the dependencies in and between models can only be captured in tools and IT systems. Therefore, **models require tools** and **IT** systems. This becomes more evident in the definition of modeling tools by Delligatti (2014, p.7): *"A special class of tools that are designed and implemented to comply with the rules of one or more modeling languages, enabling you to construct well-formed models in those languages"*.

Last but not least, there is a reciprocative relationship between humans and models. This relationship has been the focus of many research works, for example in Rhodes and Ross (2017). On the one side, **humans envision models**, that means, the modeler has a conceptual model of a system of interest in mind and expresses that in his model. It is important to note, that the reader of the model might not be the modeler and form his conception of the model and compare this conception of the model with his conception of the system of interest to validate the model. This context is further described by Giachetti (2017, p.2). After the reader validated the model, he will use the model to build his knowledge. The **model transfers** or **creates** new **knowledge** to/for the **human**. The model passes through the knowledge transformation cycle defined by Carlile and Rebentisch (2003, p.1187), consisting of knowledge storage, retrieval, and transformation.

Figure 3-3 summarizes the elements and depicted relationships between the elements and represents the complete development environment, as it is further used in this thesis.

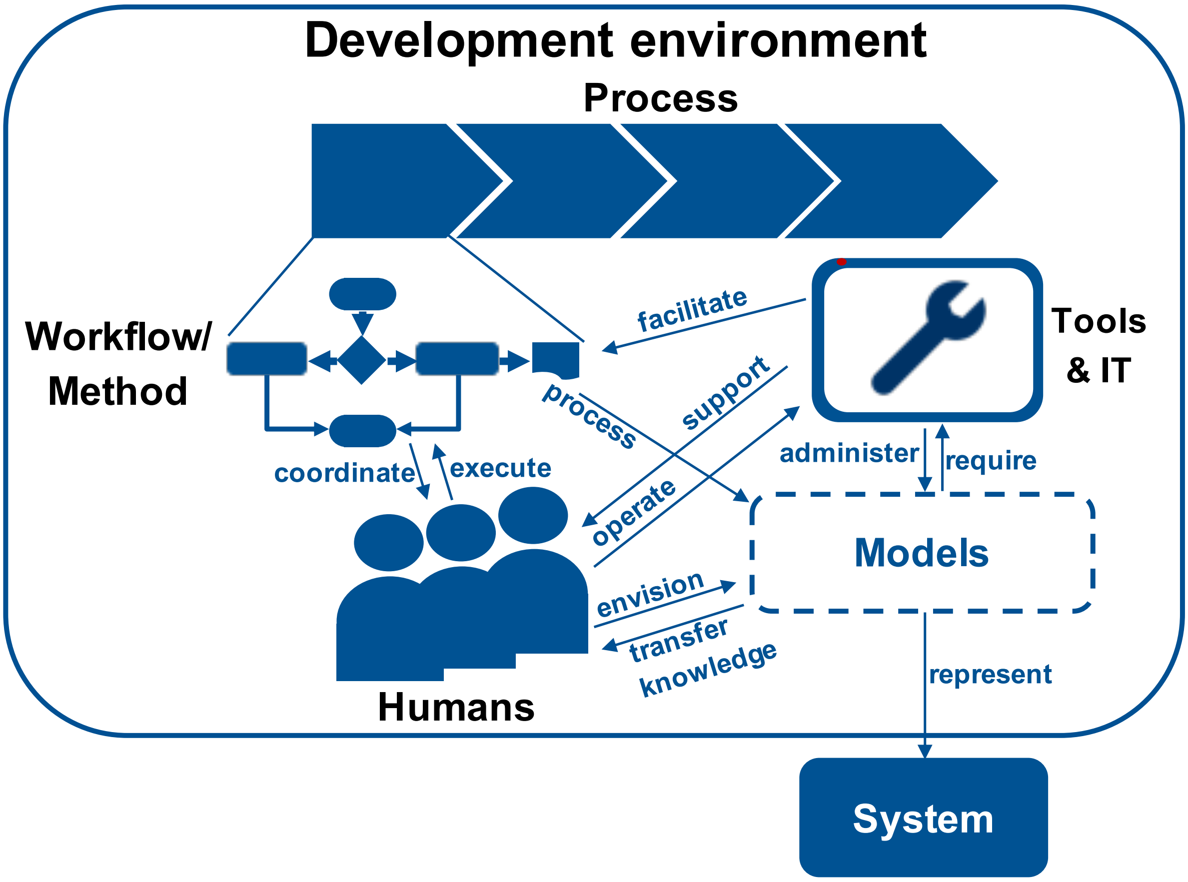

Figure 3-3: Relationships and elements forming the development environment

Insights from this subchapter about the development environment structure, the MBSE capabilities, and the MBSE potential estimation are used in a survey, which is described in the adjacent subchapter.

3.3 Survey

To get a broad overview of the current state of practice regarding MBSE and to contribute meaningful insights to the research objectives of this thesis, a survey was created and carried out in the Model-Based Systems Engineering course of the Architecture and Systems Engineering online course program. This subchapter outlines the survey context, structure, and results. The results section is subdivided in a state of practice part and a part per research objective. As the examination of success measures would have been too detailed in a survey of this size, that research objective is covered by the expert interviews described in the next subchapter.

3.3.1 Context and population

The survey was conducted in an online course spanning four weeks. The number of respondents, answering at least one question is 948. As the participants were free to leave out questions, there is a specific respondent count (N) given for each question. This section outlines the composition of the population of the survey. The composition of the population is discussed to enable the reader to form an opinion on the validity of responses and whose views they reflect.

First, regarding the validity of responses the years of experience and highest degree obtained by the participants of the survey is shown in Figure 3-4 and analyzed below.

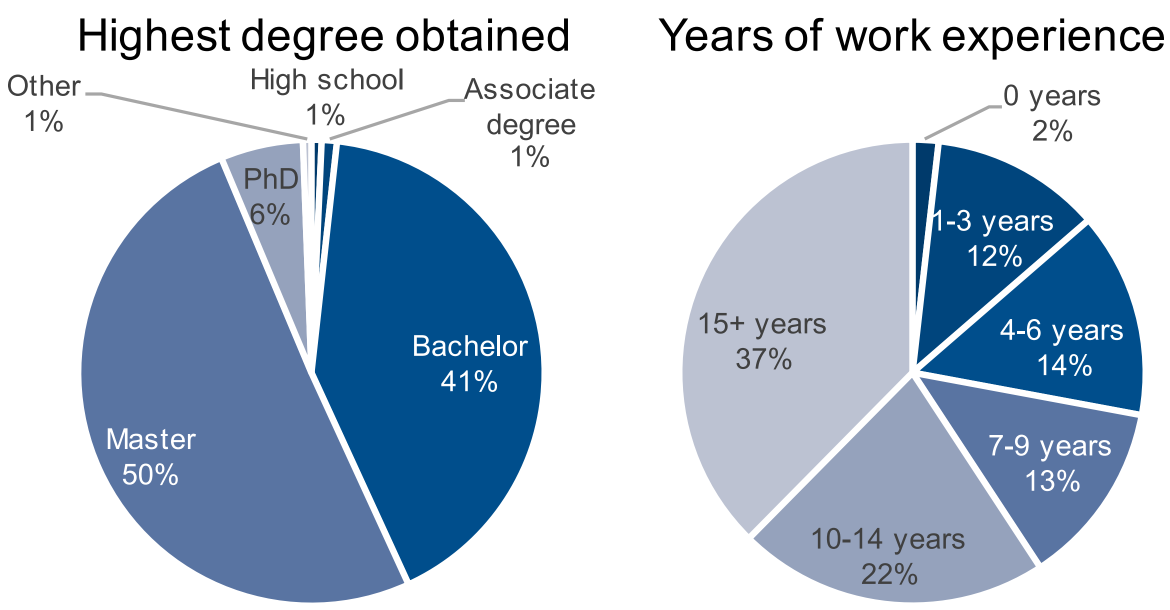

Figure 3-4: Highest degree obtained (N = 855) and years of work experience (N = 888) by the survey participants

Most of the survey participants (97 %) have a bachelor’s degree or higher. This indicates a highly educated population. More than half of the participants have 10 or more years of work experience, which underlines their ability to anticipate future changes in their field of expertise. The data shows that the **sample meets the requirements regarding the credibility of the participants**.

To understand whose views the survey reflects, the industry, field of expertise, and managerial responsibility of the participants are analyzed.

Figure 3-5 shows the industries, fields of expertise, and managerial responsibilities represented by the participants of the survey.

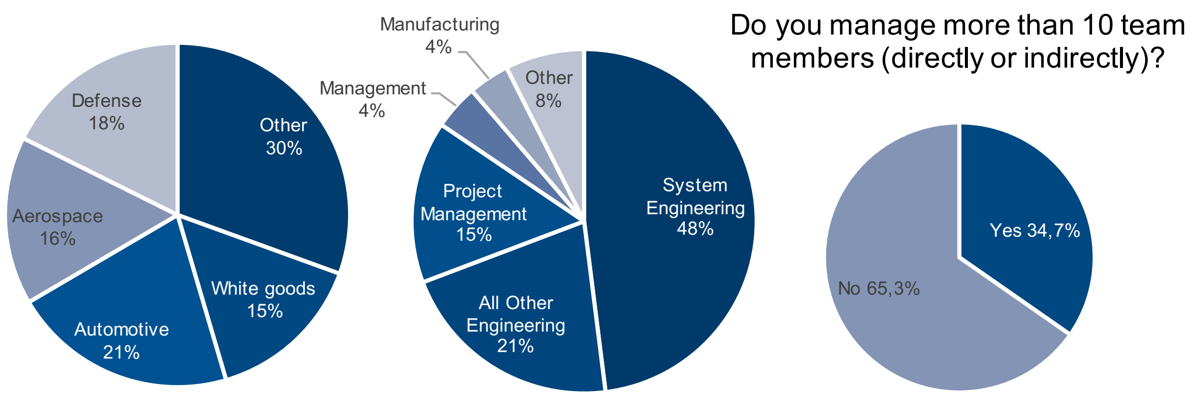

Figure 3-5: Industry (N = 550), field of expertise (N = 754) and managerial responsibility (N = 755) of survey participants

The industry has been derived from the company names the participants provided. Almost half of the participants did not provide this information. The **four industries with the biggest shares** in the population are **automotive, defense, aerospace, and white goods**. Other industries, like software/IT or consulting are represented but provide only a small percentage of participants.

In another question, the participants were asked, which of the above most closely represents their current work. **Systems engineering is the predominant field of expertise**. Other engineers and project managers represent the biggest shares of all participants not working as systems engineers. Management and manufacturing should be highlighted as represented in small shares.

As final indicator for the composition of the survey, the participants have been asked whether they manage more than ten team members (directly or indirectly). 35 % of participants manage more than ten team members directly or indirectly. The **majority** of participants rather **manages smaller teams or has no management responsibilities**.

3.3.2 Structure

After the context and population have been described, this section examines the structure of the survey. The survey was conducted parallel to four weeks of coursework covering MBSE. Figure 3-6 gives an overview of the structure of the survey and questions covered. An extract of the questions posed through a digital survey tool can be found in appendix A1.

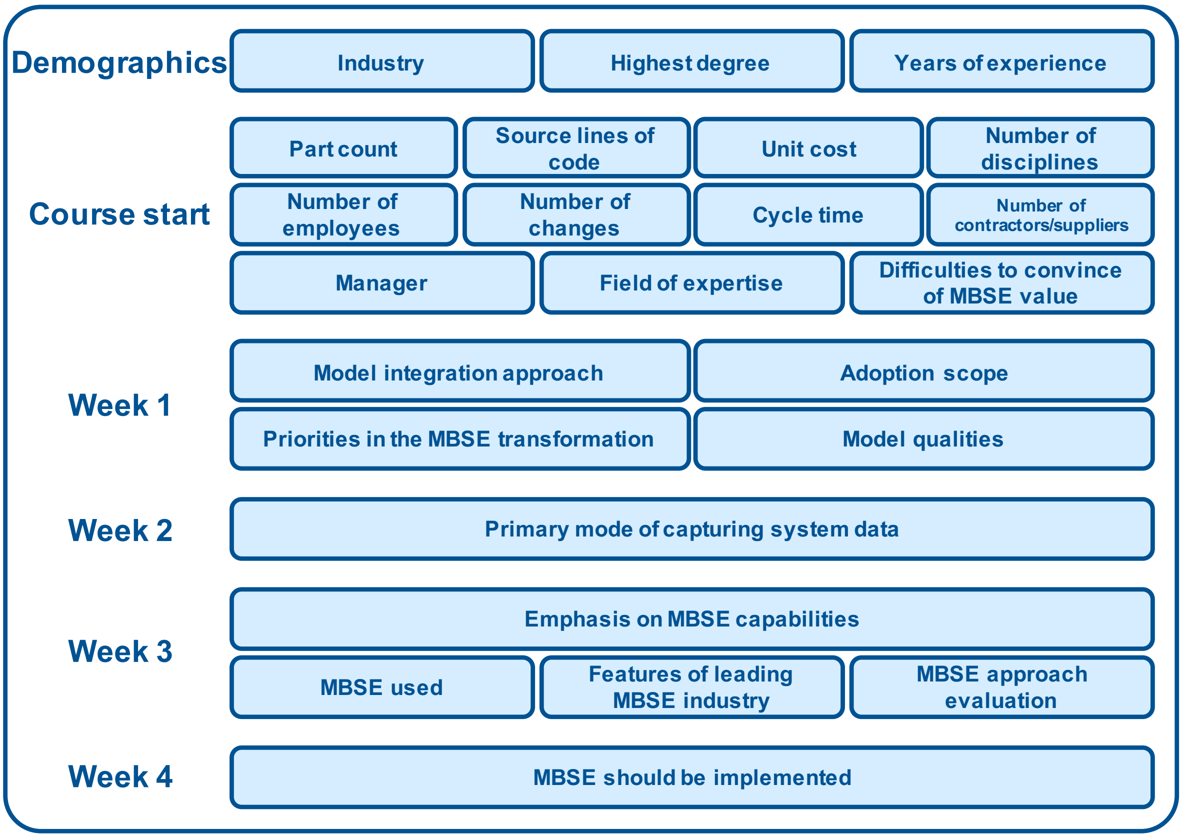

Figure 3-6: Structure of the survey

Before the course, the participants were asked to provide general information or demographics, like their company's name, their highest degree obtained, and the years of experience they have. At the start of the course, the participants were asked to classify their organization regarding eight characteristics. On top of that, their managerial responsibility, field of expertise, and difficulties they have convincing others of the value of MBSE were asked for. The first week's course content focused on the transformation towards MBSE. Therefore, their organizations modeling approach, adoption scope, and priorities in the transformation were in demand. In week two, the primary mode of capturing system data was determined. In week three, the participant's organization's emphasis on MBSE capabilities and if they currently use an MBSE approach were examined. Also, the participant's opinion on features that make the aerospace industry a leader in MBSE and if they were yet asked to formally evaluate an MBSE approach were in question. In the last week, the participants were asked if MBSE should be implemented in their organization.

The next section analyzes the obtained data from this question set. Thereby, the order of the questions is regarded as indecisive, as the responses are invariant with their appearance.

3.3.3 Analysis

The results of the survey are analyzed regarding insights contributing to the research objectives: MBSE potential estimation, excellence improvement identification, environment structure, and influence determination as well as transformation approach exploration. Before the research objectives are traced, the current state of practice in MBSE is described.

1. State of practice / Problem description

First of all, from 773 participants who were asked if their organization uses an MBSE approach, 46 % answered yes, 41 % no and 13 % are not sure. In another question, asked at the end of the course, the participants were directly asked if they themselves think that MBSE should be implemented in their organization. Of 633 participants, 68 % answered with yes, 21 % are already implementing MBSE, 3 % do not think it should be implemented and 8 % are not sure. When overlapping these two questions, two interesting aspects can be observed[1]. First, 52 % of participants (of 476) who think that MBSE should be implemented, work for an organization that is currently not using an MBSE approach. This indicates a **potential of growth for MBSE**. Second, 16 % of participants stating that they are already implementing MBSE, answered that their organization is not using an MBSE approach. This either indicates that some participants implement **MBSE in their area of influence** without considering this area being the whole organization, or that their **implementation is not mature enough** to be considered an MBSE approach. Table 3-3 shows the crosstable covering both questions.

Table 3-3: Crosstable between the use of an MBSE approach and whether an MBSE approach should be used (N = 476)

Do you think MBSE should be implemented in your organization? - Does your organization use an MBSE approach? Crosstabulation

		Does your organization use an MBSE approach?		
		Yes	No	Total
Do you think MBSE should be implemented in your organization?	Yes	165	182	347
		47,6%	52,4%	100,0%
	No	2	17	19
		10,5%	89,5%	100,0%
	Already implementing MBSE	92	18	110
		83,6%	16,4%	100,0%
Total		259	217	476
		54,4%	45,6%	100,0%

Next, the current and primary mode of capturing system data has been asked for. Figure 3-7 shows the distribution of modes of capturing system data.

[1] *There was a significant association between organizations using MBSE and whether MBSE should be implemented χ^2 (2) = 59,21, p < 0,001. (Reported as suggested by Field (2009, p.700))*

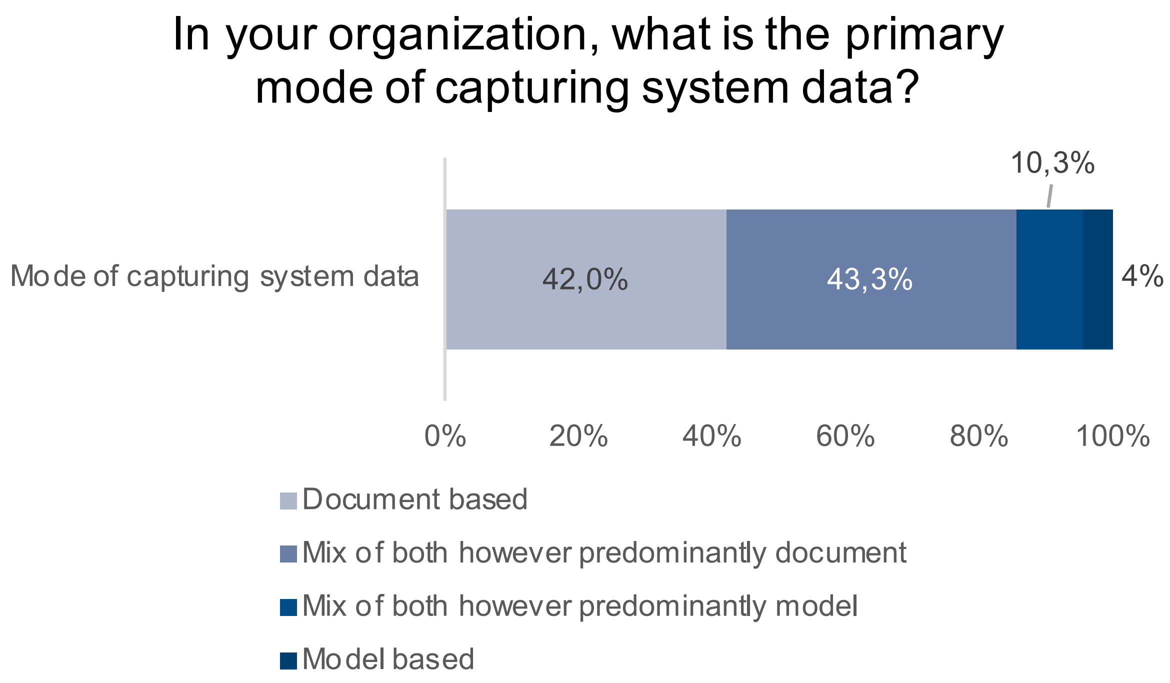

Figure 3-7: Primary mode of capturing system data in the participant's organizations (N = 776)

From 776 participants, 42 % stated that the primary mode of capturing system data in their organization is document-based. 5 % stated that it is model-based. The remaining 53 % split on a mix of both modes, with predominantly document-based in the organizations of 43 % of participants and predominantly model-based in 10 %. These numbers show that model-based or predominantly model-based is seldomly the primary mode of capturing system data. Again, indicating a **potential of growth for model-based capturing of system data and** thereby **MBSE**.

Finally, it was desired to determine why MBSE is not used in the organizations of 248 participants stating that MBSE should be used and why only 15 % of organizations are model-based or predominantly model-based. Therefore, the participants were asked in a multiple-choice question, which of six given aspects might make it difficult to convince others of the value of MBSE for their organization. The results of this question are shown in Figure 3-8.

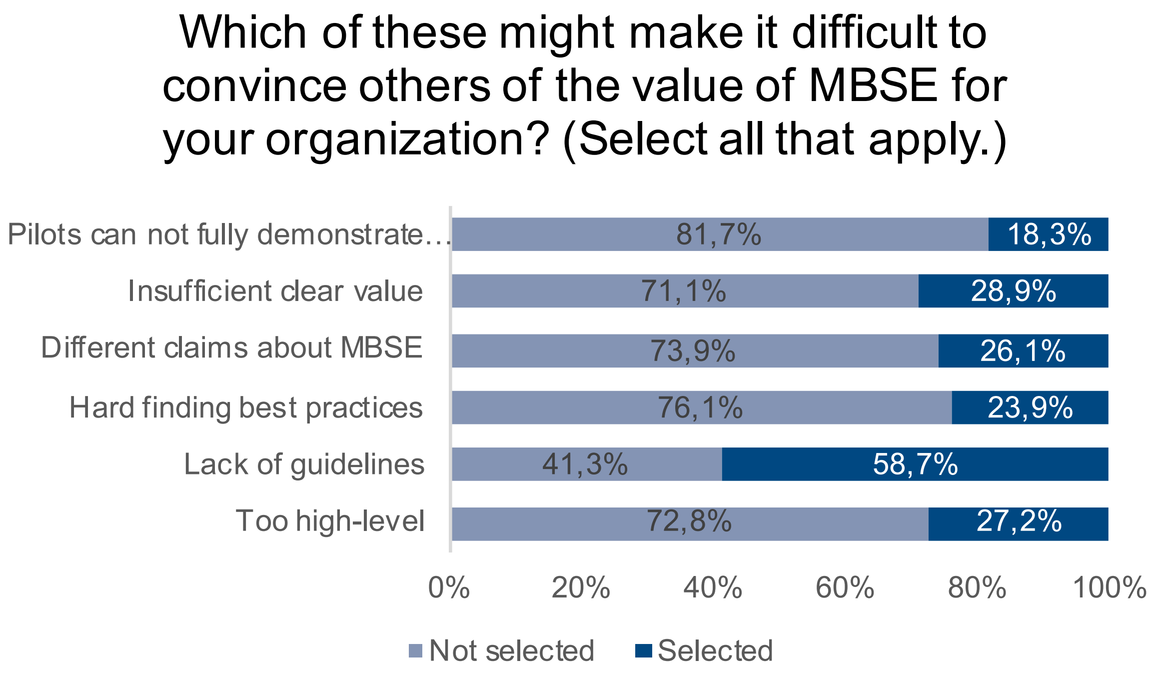

Figure 3-8: Aspects that might make it difficult to convince others of the value of MBSE for their organization (N = 356)

From 356 participants, 59 % stated that a lack of guidelines on how to implement MBSE makes it difficult to convince others of the value of MSBE for their organization. This indicates that the **implementation of MBSE** is the **key challenge** for the participants of the survey and that **future work** should **focus on providing guidelines facilitating the implementation of MBSE**. On average, one quarter of participants have issues with the other enlisted aspects.

2. MBSE potential estimation

Now, that the state of practice is clear, contributions of the survey towards the first research objective, MBSE potential estimation, are discussed.

To start with, evidence towards the assumption, that the potential through an MBSE adoption is proportional to the prevailing complexity in an organization, is provided. This assumption can be found in many literature sources, as described in section 3.2.1. Evidence that this assumption is true is not provided in the literature.

The participants of the course have been asked in a multiple-choice question, what feature or features they believe have made the aerospace industry a leader in MBSE. Provided answer possibilities were project/product complexity, regulatory environment, high development cost, and emphasis on the whole product lifecycle. The results can be seen in Figure 3-9.

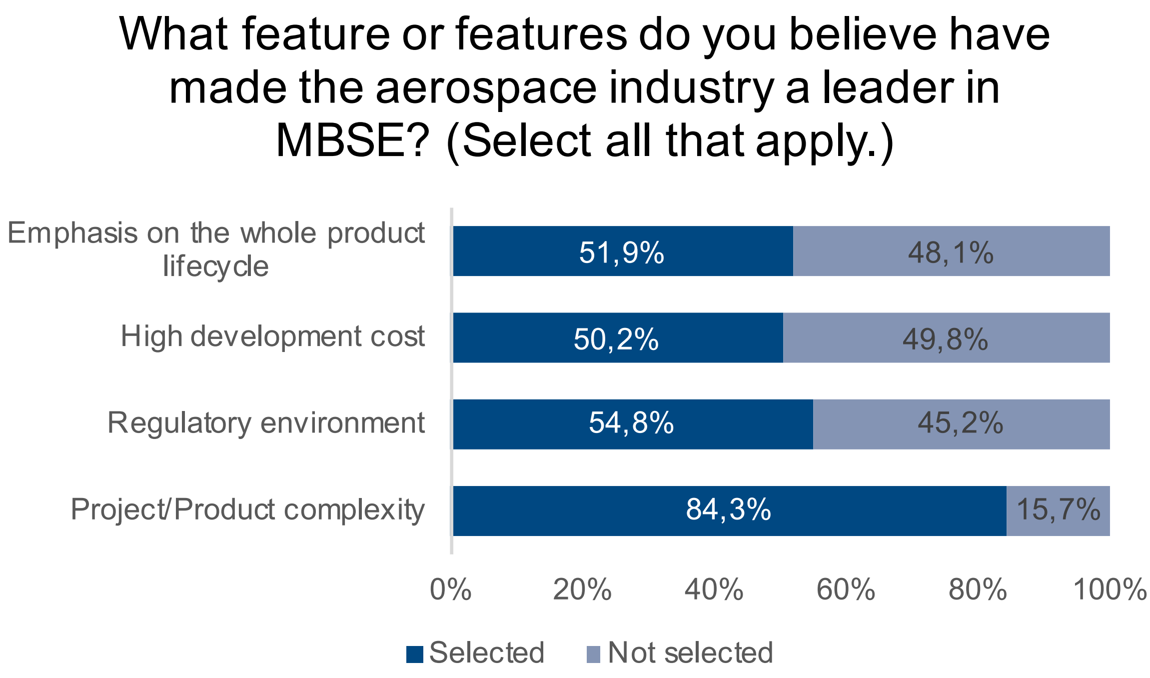

Figure 3-9: Feature or features that allegedly have made the aerospace industry a leader in MBSE (N = 715)

85 % of the N participants believe that project/product complexity have made the aerospace industry a leader in MBSE. With the other answer possibilities ranging around an approval to disapproval rate of 1, this seems to represent a significant consensus. Indicating, that the **participants see complexity as the main driver for MBSE** adoption and success.

In order to estimate the MBSE potential using the participants and our assumption, we still have to find a way to express the components indicating complexity and allow for a categorization of organizations along these components. To do so, the participants were asked to provide certain characteristics of their product and development task. The eight characteristics were elaborated in an expert discussion and are:

1. Magnitude of your organization's typical unit cost
2. Part count of your organization's typical product
3. Source lines of software code in your organization's typical product
4. Different disciplines (functional specialized groups using specific knowledge & tools distinguishing them from other groups) involved in a typical product development project in your organization
5. Length of your organization's typical development cycle
6. Approximate number of full and part time employees involved in a typical product development project of your organization
7. Number of major changes (budget cut, major change in requirements, new technology added, ...) occurring in a typical product development project of your organization
8. Number of direct contractor/supplier organizations (in a contractual relationship with your organization) for your organization's typical product development project

To analyze the provided data, a principal component analysis was conducted on the eight characteristics[2]. Table 3-4 shows the results of the principal component analysis, namely: correlations (structure matrix), factor loadings (pattern matrix), and component score coefficients.

Table 3-4: Summary of the principal component analysis for the MBSE survey (N = 148, in bold: Correlation and loading values > 0,4 as well as component score values > 0,1, in grey: positive component score values > 0,1)

	Structure Matrix			**Pattern Matrix**			**Component Score Coefficient Matrix**		
	Component			Component			Component		
	1	2	3	1	2	3	1	2	3
Number of contractors/suppliers	**0,855**	0,179	0,071	**0,909**	-0,109	-0,087	**0,311**	**-0,122**	**-0,153**
Number of employees	**0,839**	0,366	0,143	**0,843**	-0,137	0,107	**0,265**	0,035	**-0,114**
Number of changes	**0,818**	0,171	0,246	**0,813**	0,101	-0,041	**0,276**	**-0,155**	0,056
Number of disciplines	**0,801**	**0,511**	0,361	**0,685**	0,242	0,172	**0,199**	**0,131**	**0,105**
Part count	**0,688**	**0,458**	0,378	**0,571**	0,218	0,216	**0,159**	**0,115**	**0,162**
Unit cost	0,179	**0,841**	**0,424**	-0,157	**0,835**	0,274	**-0,117**	**0,610**	**0,229**
Source lines of code	**0,486**	**0,761**	-0,078	0,300	**0,724**	-0,295	0,083	**0,549**	**-0,388**
Cycle time	0,382	0,290	**0,904**	0,199	0,037	**0,857**	-0,004	-0,052	**0,870**

	Component Correlation Matrix				**Eigenvalues and Explained Variance**		
Component	1	2	3	Component	1	2	3
1	1,000	0,338	0,199	Eigenvalue	3,961	1,095	0,782
2	0,338	1,000	0,217	% of Variance	49,512	13,686	9,772
3	0,199	0,217	1,000	Cumulative %	49,512	63,198	72,970

The characteristics that **cluster** on the same components **suggest that component 1 represents organizational complexity, component 2 product-related complexity, and component 3 inertia**.

Organizational complexity increases with the number of contractors/suppliers, employees, changes, disciplines, and the part count. It is decreased through a higher unit cost, which could indicate a more systematic development approach.

Product-related complexity increases with the number of disciplines, part count, unit cost, and source lines of code. With unit cost and source lines of code being the dominant characteristics. It decreases with the number of contractors/suppliers and the number of changes. The first could be explained through an outsourcing of complexity, if contractors/suppliers are solely responsible for a module of the product. The latter is unintuitive but could be explained through the avoidance of product complexity by the development team, as a high product complexity would lead to a high change effort per

[2] *A PCA was conducted on the 8 characteristics with oblique rotation (direct oblimin). The Kaiser-Meyer-Olkin measure verified the sampling adequacy for the analysis, KMO = 0,868 ("great" according to Hutcheson and Sofroniou (1999) in Field (2009)), and all KMO values for individual items were > 0,76, which is above the acceptable limit of 0,5 (Field, 2009). Bartlett's test of sphericity $\chi 2$ (28) = 453,22, p < 0,001, indicated that correlations between characteristics are large enough for applying PCA. Three components have obtained eigenvalues over Jolliffe's criterion of 0,7 and explained an aggregated 72.97% of the variance. (Reported as suggested by Field (2009, p.671))*

change.

Inertia increases with the number of disciplines, part count, unit cost, and cycle time. With cycle time being the most dominant characteristic. It decreases with the number of contractors/suppliers, employees, and source lines of code. The first two could be justified by the workload being spread over more organizations and/or employees. The latter is harder to justify, it could be that the short development cycle and integration capabilities in the software domain create this effect.

The component scores and thereby the specific complexities for a respective organization can be computed through the following formula:

$$Component\ score_i = \sum_{j=1}^{8} Component\ score\ coefficient_{ij} \times Std.characteristic_j \qquad (3.1)$$

The standardized characteristics are computed through the specific mean and standard deviation for each characteristic, as further explained in section 4.1.

All components are positively correlated, meaning that the individual complexities increase with each other. Therefore, it is reasonable to calculate a total complexity consisting of the three specific complexities. The total complexity can be calculated through summing up all complexities/component scores:

$$Total\ complexity = \sum_{i=1}^{3} Component\ score_i \qquad (3.2)$$

The total complexity scores for the industries: white goods, automotive, aerospace, and defense, are visualized in Figure 3-11 to give a general overview of typical values.

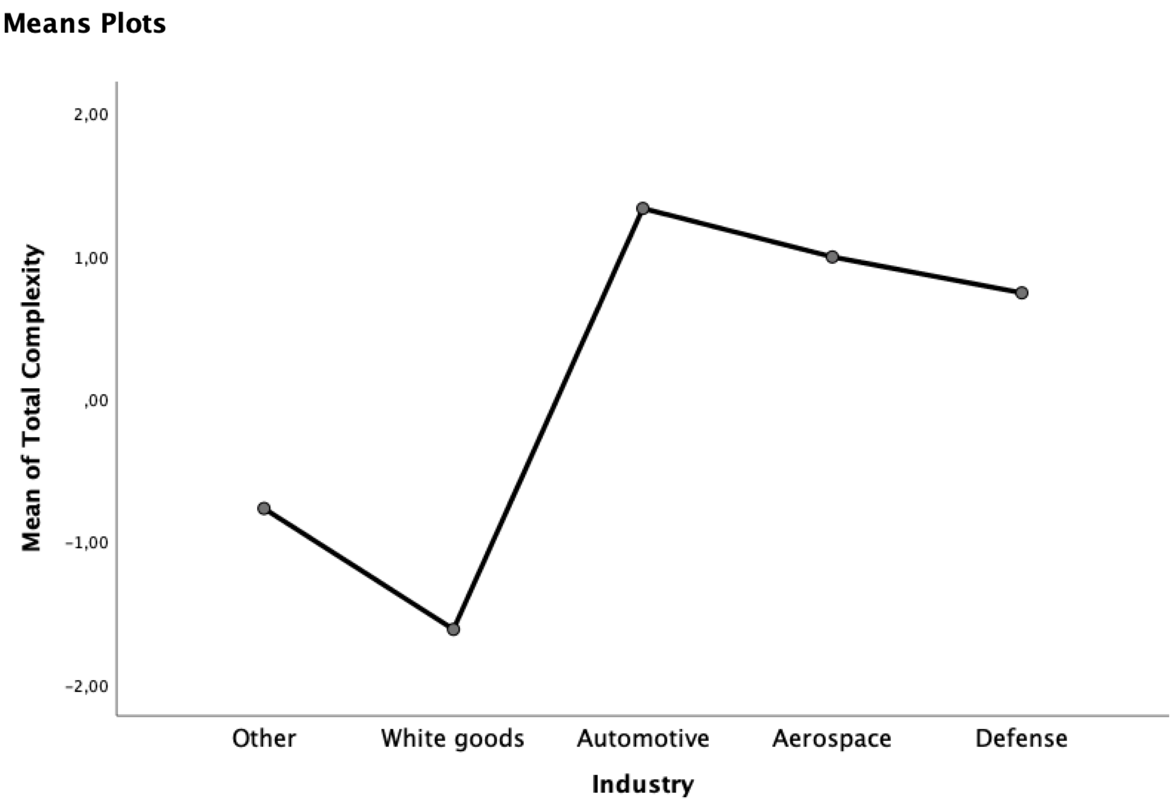

Figure 3-10: Mean of the total complexity scores of organizations in the white goods, automotive, aerospace, and defense industry

Using the defined complexities and total complexity, there is more proof for the participants and our assumption of MBSE potential being proportional to complexity. An ANOVA of the total complexity and the usage of MBSE showed a significant[3] difference of means. The difference being that **organizations using MBSE experience significantly greater total complexity than organizations not using MBSE**.

3. Excellence improvement identification

The identified excellence improvements were generalized to form the MBSE capabilities as described in section 3.2.2. These MBSE capabilities were presented to the participants in the survey and they were asked to rank their organization's emphasis on MBSE. The ranking followed the following logic. 1 being the area of focus with the greatest emphasis; 2 the second greatest emphasis, and so on, with a blank entry meaning no emphasis on that MBSE capability. Meaning that a low mean represents a high emphasis. The results are shown in Figure 3-11.

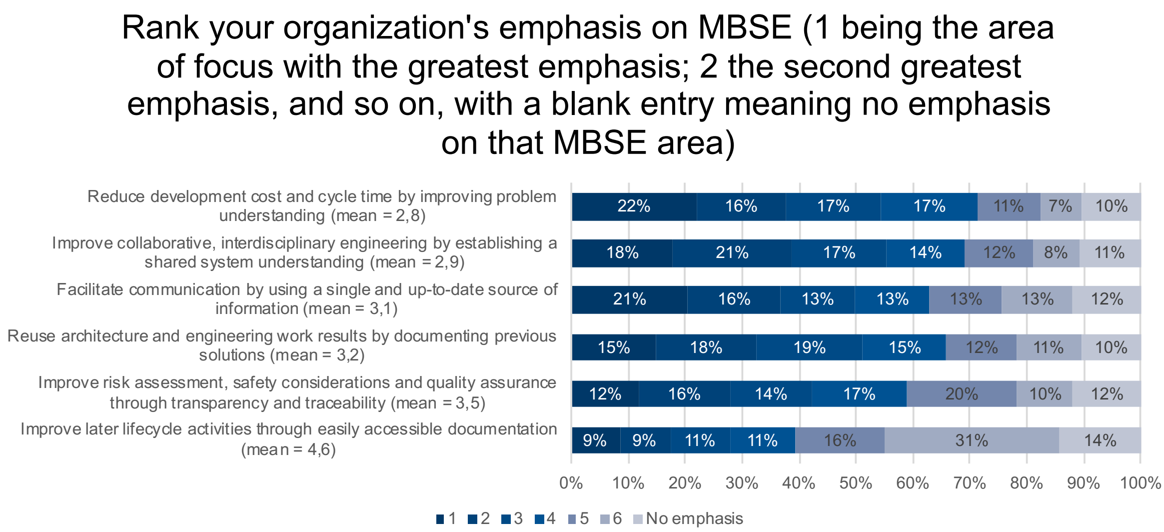

Figure 3-11: Organization's emphasis on MBSE capabilities (N = 656)

Highest emphasis for most participants is on improving problem understanding to reduce development cost and cycle time. The lowest emphasis is on improving later lifecycle decisions through easily accessible documentation. This is also the capability which is not emphasized by the most (17 %) participants.

Looking at the correlation matrix between the emphases visualized in Table 3-5, an interesting observation is that facilitate communication and improve collaboration are significantly positively correlated. Indicating that **participants emphasizing highly on facilitating communication also emphasize highly on improving collaboration** and vice versa.

[3] *There was a significant effect of MBSE usage on the level of complexity, $F(1, 120) = 5{,}355$, $p < {,}05$, $\omega^2 = 0{,}034$ (small effect). (Reported as suggested by Field (2009, p.391))*

Table 3-5: Correlation between the emphasis on MBSE capabilities (N = 505)

Pearson correlations[c]

	Facilitate communication by using a single and up-to-date source of information	Improve collaborative, interdisciplinary engineering by establishing a shared system understanding	Reuse architecture and engineering work results by documenting previous solutions	Reduce development cost and cycle time by improving problem understanding	Improve risk assessment, safety considerations and quality assurance through transparency and traceability	Improve later lifecycle activities through easily accessible documentation
Facilitate communication by using a single and up-to-date source of information	1	**,252****	**-,276****	**-,421****	**-,362****	**-,325****
Improve collaborative, interdisciplinary engineering by establishing a shared system understanding	**,252****	1	**-,223****	**-,387****	**-,296****	**-,367****
Reuse architecture and engineering work results by documenting previous solutions	**-,276****	**-,223****	1	0,003	**-,280****	**-,216****
Reduce development cost and cycle time by improving problem understanding	**-,421****	**-,387****	0,003	1	-0,047	**-,091***
Improve risk assessment, safety considerations and quality assurance through transparency and traceability	**-,362****	**-,296****	**-,280****	-0,047	1	0,044
Improve later lifecycle activities through easily accessible documentation	**-,325****	**-,367****	**-,216****	**-,091***	0,044	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

c. Listwise N=505

All of the other significant correlations are negative, meaning that increasing emphasis on one capability decreases the emphasis on another. This is a result of the ranking mode, which forces the total emphasis to be split and therefore create a certain amount of inverse proportionality. Over proportional inverse correlation can be observed between facilitate communication with improve collaboration and improve problem understanding, transparency, traceability as well as full lifecycle support. Suggesting that most **organizations emphasize either on communication and collaboration or problem understanding, transparency, traceability or the lifecycle**.

The deduced insights should facilitate the organizations selection of a focus on MBSE to motivate its implementation. The sharp selection of such a focus and motivation is necessary as the following two observations show.

The analysis of the number of emphases in relation to difficulties that make it hard to convince others of the value of MBSE, results in a significant t-Test[4]. Showing that participants stating that MBSE concepts are too high-level to convince others of the value of MBSE, have a higher number of emphases. Indicating that **a high number of emphases reduces the rigor and increases the ambiguity of MBSE concepts**, complicating its implementation.

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[4] *On average, participants stated a higher number of emphases if they have difficulties convincing others of the value of MBSE because MBSE concepts are „too high-level" ($M = 5{,}66$, $SE = 0{,}108$) than if they do not have difficulties with that aspect ($M = 5{,}31$, $SE = 0{,}094$). This difference was significant $t(173{,}46) = -2{,}432$, $p < 0{,}05$, $N = 239$; however, it did represent a small-sized effect $r = 0{,}18$. (Reported as suggested by Field (2009, p.341))*

The second observation stems from a significant chi-square test of the correlation between difficulties to convince others of the value of MBSE and whether MBSE should be implemented in the participants organization[5]. The test shows that significantly more participants who are already implementing MBSE struggle with different claims about MBSE than participants who think or do not think MBSE should be implemented. In fact, the odds of struggling with different claims about MBSE were 2,90 times higher if the participants are already implementing MBSE than if they are thinking or not thinking that MBSE should be implemented in their organization. This indicates that **different claims about what MBSE is become evident in the implementation of MBSE and not in the conceptualization** of MBSE. This again underlines the need for a sharp selection of an MBSE focus and its clear communication during the implementation.

4. Environment structure and influence determination

Similar to the ranking of the emphasis regarding the MBSE capabilities, the participants of the survey were asked to rank their organization's priorities to transform the development environment elements, similar to the ones identified in section 3.2.3. Again, the logic was 1 being the first/highest priority; 2 the second highest priority, and so on, with a blank entry meaning no priority in the transformation. Figure 3-12 shows the results of the ranking.

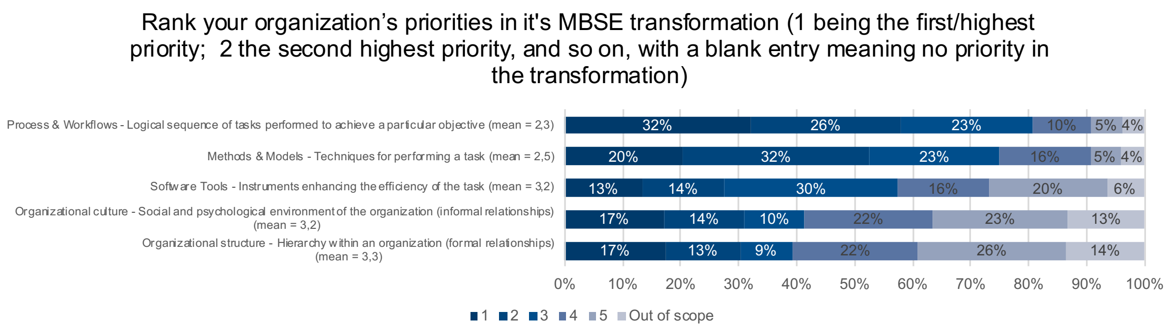

Figure 3-12: Organization's priorities in the transformation of the development environment elements (N = 693)

Process and workflows are prioritized the highest, followed by methods and models. Further behind are software tools and organizational culture and structure are the least prioritized elements. What is also interesting about organizational culture and structure is that they are out of scope in 92 and 94 (13 %) transformations. The number of transformations in which both elements are excluded is 69 (10 %). This should not overshadow the 80 % of participants who leave none of the elements out of scope. Thereby enabling a holistic transformation.

Looking at the correlations between the priorities in Table 3-6, three significant positive correlations can be observed.

[5] *There was a significant association between the difficulty „different claims about MBSE" and whether MBSE should be implemented $\chi 2$ (2) = 13,10, p < 0,005. (Reported as suggested by Field (2009, p.700))*

Table 3-6: Correlation matrix between priorities in the transformation towards MBSE (N = 554)

Pearson Correlations[b]	Process & Workflows - Logical sequence of tasks performed to achieve a particular objective	Methods & Models - Techniques for performing a task	Software Tools - Instruments enhancing the efficiency of the task	Organizational culture - Social and psychological environment of the organization (informal relationships)	Organizational structure - Hierarchy within an organization (formal relationships)
Process & Workflows - Logical sequence of tasks performed to achieve a particular objective	1	**,171****	-0,061	**-,465****	**-,444****
Methods & Models - Techniques for performing a task	**,171****	1	**,183****	**-,499****	**-,592****
Software Tools - Instruments enhancing the efficiency of the task	-0,061	**,183****	1	**-,507****	**-,465****
Organizational culture - Social and psychological environment of the organization (informal relationships)	**-,465****	**-,499****	**-,507****	1	**,234****
Organizational structure - Hierarchy within an organization (formal relationships)	**-,444****	**-,592****	**-,465****	**,234****	1

**. Correlation is significant at the 0.01 level (2-tailed).

b. Listwise N=554

First, an **increased priority on transforming methods and models increases the priority on transforming process and workflows**. This seems intuitive as a change in techniques for performing a task mostly influence the sequence in which these are performed.

Second, an **increased priority on transforming methods and models also increases the priority on transforming software tools**. Indicating the close correlation between techniques to perform the task and instruments to enhance the efficiency of the task.

Third, an **increased priority on transforming organizational culture increases the priority on transforming organizational structure**. Which could reflect that both elements are related to the organization and that changes to the organization are either of high or low priority no matter if those changes are on formal or informal relationships.

All of the other significant correlations are negative, meaning that increasing emphasis on one capability decreases the emphasis on another. This again is a result of the ranking mode, which forces the total priority to be split and therefore create a certain amount of inverse proportionality.

To facilitate the design of a target environment fulfilling the MBSE capabilities emphasized by the organization, the correlation between emphasis on the MBSE capabilities, and the priorities in the transformation has been examined, serving as a benchmark. Table 3-7 shows the correlations between the emphases and the priorities.

Table 3-7: Correlation matrix between emphasis on MBSE capabilities and priorities regarding the transformation of development environment elements (N = 376)

Pearson Correlations[c]

Rank your organization's priorities in it's MBSE transformation / Rank your organization's emphasis on MBSE	Process & Workflows - Logical sequence of tasks performed to achieve a particular objective	Methods & Models - Techniques for performing a task	Software Tools - Instruments enhancing the efficiency of the task	Organizational culture - Social and psychological environment of the organization (informal relationships)	Organizational structure - Hierarchy within an organization (formal relationships)
Facilitate communication by using a single and up-to-date source of information	-0,055	0,056	0,061	0,027	-0,078
Improve collaborative, interdisciplinary engineering by establishing a shared system understanding	0,034	**,122***	0,054	**-,112***	-0,056
Reuse architecture and engineering work results by documenting previous solutions	-0,044	-0,041	**-,137****	**,129***	0,057
Reduce development cost and cycle time by improving problem understanding	-0,002	0,023	0,036	-0,026	-0,022
Improve risk assessment, safety considerations and quality assurance through transparency and traceability	-0,051	**-,125***	-0,007	0,016	**,129***
Improve later lifecycle activities through easily accessible documentation	**,130***	-0,037	-0,009	-0,048	-0,024

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
c. Listwise N=376

The emphasis on four capabilities significantly correlates to priorities regarding the transformation of development environment elements.

First, a **high emphasis on improving collaboration significantly increases the priority of models and methods, while significantly decreasing the priority of organizational culture** in the transformation towards MBSE. This could indicate that systematic methods covering most of the interdisciplinary communication are seen as alternative to informal communication and relationships covering most of the interdisciplinary communication today. Meaning that an organization tries to improve collaboration on a method basis, while informal communication and changes to the organizational culture are not a focus. Therefore, they are of low priority in the transformation.

Second, a **high emphasis on reusing architecture and engineering work results significantly increases the priority of organizational culture, while significantly decreasing the priority of software tools** in the transformation towards MBSE. This could indicate that organizations see the organizational culture with its informal relationships as more capable of leading to reuse than software tools. Therefore, a change of culture is more necessary than a change of software tools, leading to the observed prioritization.

Third, a **high emphasis on improving transparency and traceability significantly increases the priority of organizational structure, while significantly decreasing the priority of methods and models** in the transformation towards MBSE. Suggesting that the responsibilities and thereby the organizational structure is of increased interest in the transformation towards more transparency and traceability, leading to a better assessment of risks and better quality. On the other hand, the low priority of methods and models could indicate that the organizations see less potential for improving transparency and traceability in methods and models than in organizational structure and therefore trade one off against the other.

Fourth, a **high emphasis on improving later lifecycle activities significantly increases the**

priority of process and workflows in the transformation towards MBSE. This is intuitive as the later lifecycle phases have to be included as objectives into the process and workflows.

5. Transformation approach exploration

Finally, the influence of different factors of a transformation approach is to be explored to support the decision for a suitable and successful approach. Therefore, two major factors determining the transformation approach are further examined. These are the scope of the transformation and the approach to modeling.

Modeling approach

Regarding the modeling approach, there are two extreme scenarios: Tying together existing models or building a new model landscape from ground up. These two extreme scenarios are further examined on purpose, as these extreme cases best highlight the strengths and weaknesses of the approaches. Insights about the strengths and weaknesses of the extreme approaches should allow organizations to find the best approach for them, which in most cases is a mixture of both extreme scenarios in a moderate approach.

The exact single-choice question regarding the modeling approach was: for your organization, which approach is more likely to be adopted? The two answer possibilities were ground up/clean sheet or tying existing models together. The results are shown in Figure 3-13.

Figure 3-13: Most likely modeling approach used by the organizations (N = 658)

As the results show, **tying existing models together is the predominant approach** regarding model integration.

For two MBSE capabilities, t-tests show a significant difference in emphasis mean between the two modeling approaches[6]. **Organizations who are more likely to tie existing models together have significantly greater emphasis on reusing architecture and engineering work results as well as improving problem understanding**. Both results are justifiable and include a recommendation. First, as the current models of the organization are one of the work results, emphasized to be reused they should be retained. Second, the existing models contain most of the problem understanding and therefore have to be retained to improve the current problem understanding.

Another t-test between the modeling approach and the number of emphasized MBSE capabilities showed a significant result[7]. **Organizations who are more likely to tie existing models together have a significantly higher number of emphasized MBSE capabilities**. This practice can become problematic, as tying existing models together imposes many constraints on the implementation approach, which at the same time should comply with multiple MBSE capabilities. Requiring a sophisticated MBSE implementation approach.

Further insight into modeling approaches stems from a significant chi-square test between the modeling approach and the question if participants have ever been asked to formally evaluate or critique an MBSE approach[8]. **Participants from organizations who are likely to adopt a clean sheet modeling approach have more likely been asked to evaluate or critique an MBSE approach**. In fact, the odds of evaluating or criticizing an MBSE approach were 1,87 times higher for clean sheet approaches being more likely than for tying approaches. Therefore, clean sheet approaches seem to be carried out more thoughtfully. But there is potential for formally evaluating and criticizing MBSE approaches for both modeling approaches, as evaluation numbers are low.

The approaches to modeling have been examined regarding their influence on the difficulty of achieving the model qualities:

- Linked to decision support,
- Model credibility,
- Clear scope,
- Verification and validation with models,
- Understandable and well-organized,
- Analyzable and traceable,

[6] *On average, participants have significantly greater emphasis on reusing architecture if they are more likely to tie existing models together ($M = 3,41$, $SE = 0,096$) than if they are more likely to use a clean sheet approach ($M = 3,80$, $SE = 0,144$). This difference was significant $t(353,91) = 2,242$, $p < 0,05$, $N = 530$; however, it did represent a small-sized effect $r = 0,12$. On average, participants have significantly greater emphasis on improving problem understanding if they are more likely to tie existing models together ($M = 3,03$, $SE = 0,099$) than if they are more likely to use a clean sheet approach ($M = 3,41$, $SE = 0,142$). This difference was significant $t(530) = 2,279$, $p < 0,05$; however, it did represent a small-sized effect $r = 0,10$. (Reported as suggested by Field (2009, p.341))*

[7] *On average, organizations have a significantly higher number of emphasized MBSE capabilities if they are more likely to tie existing models together ($M = 5,45$, $SE = 0,062$) than if they are more likely to use a clean sheet approach ($M = 5,19$, $SE = 0,110$). This difference was significant $t(310,55) = -2,093$, $p < 0,05$; however, it did represent a small-sized effect $r = 0,13$. (Reported as suggested by Field (2009, p.341))*

[8] *There was a significant association between the modeling approach and the evaluation or critique of an MBSE approach $\chi 2\ (1) = 6,10$, $p < 0,05$. (Reported as suggested by Field (2009, p.700))*

- Data extrapolation,
- Complete relative to scope and intended purpose,
- Internally consistent,
- Verifiable,
- Validation,
- Model fidelity,
- Elegant,
- Well formed for optimization,
- Avoid optimizing on a black box,
- Availability of interfaces,
- Reusable

There was a significant positive chi-squared value for both modeling approaches (ground up/clean sheet[9] and tying existing models together[10]) with respectively one model quality (complete relative to scope and intended purpose and model credibility).

The data showed that significantly more participants stating that a clean sheet approach to modeling is more likely for their organization struggle with models being complete relative to scope and intended purpose than if tying together existing models is more likely. This seems intuitive, as the scope and intended purpose of the newly created models has to be defined and understood in the model creation. It seems that **defining the scope and understanding the intended purpose** of the models **in model creation is challenging** for practitioners.

The other significant association, model credibility being a more difficult to achieve model quality in tying existing models together compared to clean sheet modeling, can be interpreted in two ways. First, the association might indicate that the **lack of credibility of the legacy models is carried over** to the newly connected model landscape. Second, a loss of **credibility** in the new model landscape could be **lost in the connection of the models**. For example, wrong or unlikely assumptions justifying the connections can lead to a loss of credibility. Also, the model landscape's credibility could be undermined by the weakest model in it, similar to the weakest link in the chain.

Scope of the adoption

Regarding the adoption scope, the participants have been asked about the primary approach their organization uses in its MBSE adoption. Answer possibilities were (1) adoption by individuals in their workflows, but not at the project or organizational level, (2) on a project

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[9] *There was a significant association between the difficult to achieve model quality complete relative to scope and intended purpose and the modeling approach "clean sheet" $\chi 2$ (1) = 4,53, $p < 0,05$. The odds of complete relative to scope and intended purpose being a difficult to achieve model quality were 1,49 times higher for using a clean sheet approaches being more likely than tying existing models together. (Reported as suggested by Field (2009, p.700))*

[10] *There was a significant association between the difficult to achieve model quality model credibility and the modeling approach $\chi 2$ (1) = 13,79, $p < 0,001$. The odds of model credibility being a difficult to achieve model quality were 1,94 times higher for tying approaches being more likely than clean sheet approaches. (Reported as suggested by Field (2009, p.700))*

by project basis, but not organization-wide, (3) as part of a larger transformation program or (4) we are not yet adopting MBSE. The responses are shown in Figure 3-14.

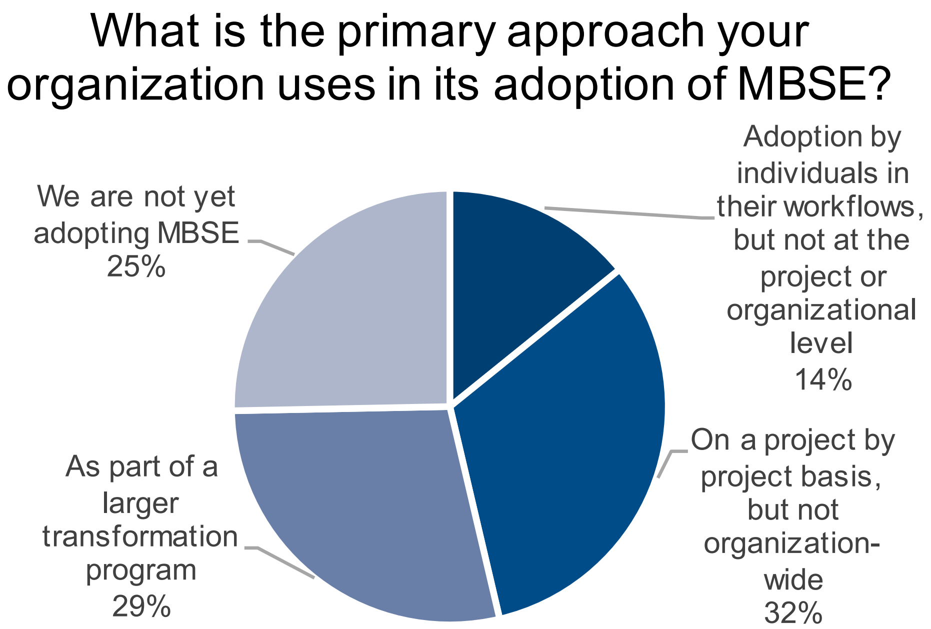

Figure 3-14: Scope of the organizations' MBSE adoption (N = 818)

As the figure shows, **project-wide and organization-wide scopes are equally prevalent**. Adoption by individuals is less common but still significant. A quarter of the participants is not yet adopting MBSE and is therefore excluded from further analyses of the adoption scope.

For the scope of the adoption in regard to the difficult to achieve model qualities, there have been three significant associations with model credibility, verifiable, and well-formed for optimization.

Model credibility is significantly low in a project-wide adoption[11]. Model credibility is low in project-wide adoption approaches because **the model's validity has to be evaluated in the respective project's context** by the model user. In individual approaches there's one known responsible for the credibility and in organization-wide approaches model credibility is the responsibility of the organization.

[11] There was a significant association between the difficult to achieve model quality model credibility and the adoption scope $\chi2$ (2) = 6,90, p < 0,05. The odds of model credibility being a difficult to achieve model quality were 1,84 times higher for project-wide adoption than for adoption by individuals. (Reported as suggested by Field (2009, p.700))

The difficulty of creating verifiable models increases significantly with the size of the adoption scope[12]. An intuitive explanation for this observation is that the difficulty of creating verifiable models increases with the adoption scope because **more extensive models are more difficult to evaluate**.

Well-formed for optimization is a significantly difficult to achieve model quality in project-wide approaches[13]. Well-formed for optimization could be a difficult to achieve model quality in project-wide approaches, because the **model's content is configured specific to the project**. In individual approaches, one responsible overlooks both creation and optimization of the model, while the content of the model is kept constant and consistent in organization-wide approaches.

In summary, using a project-wide adoption approach could have negative effects on the models being credible and well-formed for optimization. Difficulties in verifying models increases with the extent of the models and thereby with the scope of the adoption. The next subchapter covers the analysis of the expert interviews.

3.4 Expert interviews

The broad insights gained in the literature study and the survey are enriched with detailed insights from the industrial applications of MBSE. Therefore, ten interviews with industry experts have been conducted. The interviews with six participants from the automotive industry and four participants from the commercial vehicle industry had a duration of 30 to 90 minutes. The semi-formal interviews followed the interview guideline in appendix A2. Central aspects of the interviews were the objectives the organizations are trying to achieve with MBSE, correlating metrics, the validation of the development environment structure derived from literature and changes in this environment caused by the MBSE transformation. The interviews started off with an introduction of the participants and a presentation of the research objectives, MBSE fundamentals, and guideline concept, followed by an example. Facilitating the participant's understanding of the question's scope and context. Insights gained from the interview are outlined in the following sections: objectives, metrics, environment evaluation, and environment changes.

[12] *There was a significant association between the difficult to achieve model quality verifiable and the adoption scope $\chi 2$ (2) = 8,99, p < 0,05. The odds of verifiable being a difficult to achieve model quality were 4,55 times higher for organization-wide adoption than for adoption by individuals. (Reported as suggested by Field (2009, p.700))*

[13] *There was a significant association between the difficult to achieve model quality well-formed for optimization and the adoption scope $\chi 2$ (2) = 11,95, p < 0,01. The odds of well-formed for optimization being a difficult to achieve model quality were 2,56 times higher for project-wide adoption than for adoption by individuals. (Reported as suggested by Field (2009, p.700))*

3.4.1 Objectives

The participants were presented with the MBSE capabilities derived from literature (see section 3.2.2) and asked to map them to their current efforts and objectives to introduce model-based systems engineering by stating their importance and how they are pursued in practice. To support the participants mapping of the objectives to their actions regarding MBSE, exemplary actions were added. For example, the objective "facilitate communication" was supplemented by the action "using a single and up-to-date source of information". The answers for each objective are presented in arbitrary order and are summarized in a short insight paragraph.

Facilitate communication

MBSE facilitates communication among stakeholders through providing a single, up-to-date, and rigorous source of information. This objective is emphasized as **very important** by most of the participants.

Half of the participants pursue this objective through establishing a **single-source-of-truth, administrating data** from different sources and **providing** it in an **ordered manner**. The participants stressed that the single-source-of-truth should align the different states of knowledge in existence. An idea to implement this is through creating a versioning system. The single-source-of-truth should also represent one point and overview of all kinds of data and be characterized through a low response time on inquiries. Some participants can imagine a decentralized single-source-of-truth, where every department has its central and digital system model along with an organization-wide connection of these in a network. That might also represent a necessary intermediate state, as multiple, decentralized single-source-of-truths currently exist in pilots.

Other participants focus on using **models** to make **communication** more **efficient** and **effective** through reducing unnecessary communication paths and increasing comprehension. They try to accomplish that by specifying the coordination need upfront by leveraging product architecture and systems engineering techniques. This should allow them to steer the necessary coordination efforts and eliminate unnecessary calls and meetings between disciplines. To make communication more effective, participants seek to employ more models which support comprehension through visualization. An exemplary model for this task is given with a function-oriented system model facilitating interface discussions.

Table 3-8 summarizes the objectives and means to achieve them, regarding the capability "Facilitate communication".

Table 3-8: Objectives and means to achieve them, regarding the capability "Facilitate communication"

Facilitate communication	**Very important**
Objective	Means
Administrate latest data centrally	Single-source-of-truth
Provide data in an ordered manner	Single-source-of-truth
Communicate more effective and efficient	Models

Improve collaboration

Through MBSE, collaboration and interdisciplinary work is improved by establishing a shared system understanding. This is seen as more applicable in hardware than in software development because of the higher amount of involved disciplines and is **not** the **immediate focus** of MBSE efforts.

In practice, **interdisciplinary work and collaboration** between different stakeholders is **increased** and **silos** are **reduced** through using a **functional structure**. The functional structure is seen as superior to the component-oriented structure in supporting the collaboration between the module responsible and the functional discipline (e.g. simulation). Likewise, the collaboration between module responsibles is improved.

The improved collaboration is extended **over** the **organizational boundaries**, across which a **shared understanding** is **ensured** through sharing **models**. The suppliers/contractors demand this sharing from the original equipment manufacturer, as there first task usually is creating a model from the specifications. If they would receive a model, this step would become obsolete.

Finally, **models** help to **identify and engage all the right disciplines** to faster approach the best performing solution. This becomes especially valuable in development programs with a large number of involved disciplines.

Table 3-9 summarizes the objectives and means to achieve them, regarding the capability “Improve collaboration”.

Table 3-9: Objectives and means to achieve them, regarding the capability "Improve collaboration"

Improve collaboration	**Less important**
Objective	Means
Increase collaboration and reduce silos	Functional structure
Ensure shared understanding across organizational boundaries	Models
Identify and engage all the right disciplines	Models

Enable reuse

MBSE enables the reuse of architecture and engineering work results by documenting previous solutions in a more standardized way and leveraging the increased knowledge captured in models.

The same effect and focus can be observed in practice, where solutions are shared in a **standardized, solution-neutral wording** using **libraries**. Ideally these libraries are function-oriented, to allow the engineer to assess multiple concepts before committing to a module. Also, the solutions should be cataloged in a standardized but meaningful form.

The libraries utilize **knowledge**, that is made explicit, documented, made accessible, and then **transferred** through **models**. Therefore, models are a central mean to the reuse of knowledge and engineering work results and should be addressed when it comes to increasing the current degree of modularization.

Another focus regarding this capability is the **management of product complexity** by modularizing the product and reusing the resulting understanding in form of an **architecture** across projects. The developed architecture helps to achieve effects of scale and eliminates most of the product configuration and adaption efforts.

Table 3-10 summarizes the objectives and means to achieve them, regarding the capability "Enable reuse".

Table 3-10: Objectives and means to achieve them, regarding the capability "Enable reuse"

Enable reuse	**Important**
Objective	Means
Standardize and keep wording solution-neutral	Libraries
Transfer knowledge	Models
Manage product complexity	Architecture

Improve transparency and traceability

The dependencies of a model and its context as well as the opportunity to rapidly cycle design concept models are used to improve the transparency and traceability.

In practice, the focus is on **increasing traceability and accessibility** of systems by using **model dependencies** to automate tests and link further context. Further context could for example be given through requirements in test cases. According to industry experts, the automated tests and the a priori knowledge of dependencies both improve product quality. Helping to replace expensive hardware tests through model-based tests.

Transparency of the system is also **increased** trough enriching the information or data stored in the model with its history. Explaining the source of and assumptions in the **data**. Thereby giving the user of this information necessary context to assess the quality of the data at hand and evaluate its applicability for the user's purpose.

Along dependencies, a **functional product structure** is leveraged to ensure functional **safety** standards and **assure quality**. Most of the systematic safety and quality assurance methods build on a functional description of the product (e.g. Failure mode and effect analysis (FMEA)). Table 3-11 summarizes the objectives and means to achieve them, regarding the capability "Improve transparency and traceability".

Table 3-11: Objectives and means to achieve them, regarding the capability "Improve transparency and traceability"

Improve transparency and traceability	**Very important**
Objective	Means
Increase traceability and accessibility	Model dependencies
Increase transparency	Data quality
Assure safety and quality	Functional product structure

Support the full lifecycle

Easily accessible and maintained documentation provided by model-based engineering improves later lifecycle activities. This is **not** the **main focus** of practical MBSE efforts.

However, a more **continuous development** is pursued by including the **curation of older systems versions** in the development of new versions. This also increases reuse evaluation and actual reuse of artifacts as curation effort is traded against new development effort.

Also, **usage data** is **fed back** into development through using **models** as the structure for the creation of digital twins. The model provides the necessary dependencies between data points to facilitate the interpretation of the collected field data. The model can also be used to verify assumptions made during development. Leading to a learning development organization.

Table 3-12 summarizes the objectives and means to achieve them, regarding the capability "Support the full lifecycle".

Table 3-12: Objectives and means to achieve them, regarding the capability "Support the full lifecycle"

Support the full lifecycle	**Less important**
Objective	Means
Develop continuously	Curation of older versions
Feed back usage data	Models

Foster holistic problem understanding

MBSE methods improve the problem understanding, by creating in-depth knowledge about the system and its application from multiple perspectives.

In practice, the **number and cost of problems** in later lifecycle phases is **reduced** by **pushing up** development **cycles** to earlier phases. This is enabled through describing problems in abstract models covering only the governing attributes of the solution. These attributes can then be traded against each other until an optimal solution is achieved.

Not only the development cycle is accelerated, models including **multiple viewpoints accelerate** the **reaching** of **consensus** in development decisions. As all involved parties are able to follow the arguments of the others in the model, a consensus can be reached much faster than if every party thinks in their respective model.

Multiple viewpoints also support **enriching information** with context (e.g. their legacy), increasing the overall understanding. This context can be the use case to a requirement or the simulation type and parameters to a force vector. The exemplary information provides a larger information basis for the design decision, thereby increasing the chances of choosing the right option.

Finally, **In-house capabilities** are **increased** through the improved problem understanding. The increased understanding of the development problem allows for a more focused technology scouting and the improved **anticipation** of **technology maturity.** This results in a lasting in-house resource built-up in that respective technology.

Table 3-13 summarizes the objectives and means to achieve them, regarding the capability

“Foster holistic problem understanding”.

Table 3-13: Objectives and means to achieve them, regarding the capability "Foster holistic problem understanding"

Foster holistic problem understanding	**Important**
Objective	Means
Reduce number and cost of problems in later phases	Pushing up cycles
Accelerate consensus reaching	Multiple viewpoints
Enrich information	Multiple viewpoints
Increase in-house capabilities	Anticipated technology maturity

This is just a selection of objectives derived from 10 expert interviews. The variety of objectives and means to achieve them is much higher in practice. As the described objectives where similar between the companies, the objectives seem to be aligned within the automotive and commercial vehicle industries. Table 3-14 gives a final overview of all described objectives with their respective means for every MBSE capability.

Table 3-14: Overview of all described objectives with respective means for every MBSE capability

Objective	Means
Facilitate communication	**Very important**
Administrate latest data centrally	Single-source-of-truth
Provide data in an ordered manner	Single-source-of-truth
Communicate more effective and efficient	Models
Improve collaboration	**Less important**
Increase collaboration and reduce silos	Functional structure
Ensure shared understanding across organizational boundaries	Models
Identify and engage all the right disciplines	Models
Enable reuse	**Important**
Standardize and keep wording solution-neutral	Libraries
Transfer knowledge	Models
Manage product complexity	Architecture
Improve transparency and traceability	**Very important**
Increase traceability and accessibility	Model dependencies
Increase transparency	Data quality
Assure safety and quality	Functional product structure
Support full lifecycle	**Less important**
Develop continuously	Curation of older versions
Feed back usage data	Models
Foster holistic problem understanding	**Important**
Reduce number and cost of problems in later phases	Pushing up cycles
Accelerate consensus reaching	Multiple viewpoints
Enrich information	Multiple viewpoints
Increase in-house capabilities	Anticipated technology maturity

3.4.2 Metrics

After the participants stated their respective objectives regarding the application of MBSE, they were asked to complement these objectives with metrics measuring their achievement. As examples for possible metrics, return-on-invest (ROI), development cycle time, information latency time, and number of distributed document versions were given. Before examining the capability-related answers, more general answers shared by the experts are highlighted.

First of all, the majority of experts believes that to lead the change towards increased use of systems engineering techniques and models in engineering, one has to trust in their capabilities. That stems from their experience, that most of the benefits achieved through MBSE are not quantifiable in hard metrics. They emphasized that the first step and most focus should be on changing the mindset of colleagues and not on cost and time savings. All participants agreed that a proof of success is required after a certain time but pointed out that getting to this proof is a complicated task. Two central, non-exclusive points why this is the case are briefly described in the following.

As the development projects are complex and unique, there is no baseline to compare against. The state without using the newly introduced methodology is not presentable and can only be interpolated with data from previous projects. One way to cope with this challenge is to compare the project with the new methodology to a similar completed project and compensate for their differences. Another way, preferred by the experts, would be to monitor trends in certain metrics while implementing the new methodology.

Another issue that might occur is that the allocation of the effort and benefits interferes with the success to be proofed. As Madni and Purohit (2019, p.12) show, the lifecycle costs will increase with the introduction of MBSE in earlier phases and decrease in later phases. Given that an organization uses cost centers for the allocation of costs, the cost of the centers in concept and preliminary design will increase, while the cost of the centers in detailed design/manufacturing will decrease. If this effect is not explained by coupling effort and benefit, the model creating effort in the preliminary design phase will be shut down because it increased the cost locally without visible local benefit.

These two points show that it is indispensable to anticipate the effects of the MBSE transformation and closely monitor the right metrics parallel to its implementation. The next section describes a selection of metrics that the interviewed experts use to keep track of the success of their MBSE implementation.

Again, the capability-related metrics are presented in arbitrary order and are explained briefly. To further specify the metrics, three attributes are assigned. The dedicated effect to measure, the kind of metric (binary, ratio, amount), and the effort to measure this metric (high, medium, low).

Facilitate communication

Table 3-15: Overview of derived metrics to measure the facilitation of communication

Facilitate communication			
Metric	Measured effect	Kind	Effort
Number of users	Scope of sharing knowledge	Amount	Small
Time spend engineering	Value creation	Amount	Medium
Time to find information	Value creation	Amount	High
Ratio of in-house value creation	Change in capacity	Ratio	Small
Ratio of active communication paths	Communication performance	Ratio	Medium
Time spend preparing/editing data	Communication performance	Amount	Medium
Internal customer satisfaction ratio	Quality of communication	Ratio	-

- **Number of users**

  Like with a social network, the use of a model for communicating and sharing knowledge increases with the number of users using it. Therefore, the number of users of a model can be seen as a measurement of the **scope of sharing knowledge** using this model. The number of users does not have to be measured in people, it can also be measured in departments, plants etc.. This metric measurable with **low** effort and represents an **amount**.

- **Time spend engineering**

  To recall from section 3.2.2, engineers spend a lot of time communicating, coordinating, and acquiring information. These activities are not directly value creating and hinder the engineer from his actual tasks. If MBSE succeeds in facilitating communication, coordination, and acquiring information, the time spend on these should decline and time spend on **value creating** engineering **work** should increase. This can be measured with **medium** effort through specific time tracking and represents an **amount**.

- **Time to find information**

  In contrast to the measuring of the ratio of times engineers spend actually engineering, the time to communicate, coordinate, and acquire information can be measured directly. This can be achieved through a very detailed time tracking system, which is reflected in a **high** effort to measure this **amount**. Again, its decrease should reflect an **increase** in time spend on **value creating work**.

- **Ratio of in-house value creation**

  Closely linked to its predecessor is this metric. If the engineering work to communication ratio increases, the individual engineer's workload can be increased, increasing the overall **capacity of the department**. This can lead to the increase of in-house value creation. This again reflects the success of the MBSE implementation and can be measured in a **ratio** by summing up internal and external capacities with a **small** effort.

- **Ratio of active communication paths**

  Discussing the use of a model for sharing certain information will disclose all information stakeholders. Information stakeholders being information producer, observer, and user. The past ways of sharing this information with its benefits and deficits will become clear and can be analyzed and compared against the **performance** of the model and thereby **communication practices**. A metric which is currently used in practice is the ratio of active to passive communication paths. It can be captured in a Domain structure matrix (DSM), which Kreimeyer (2010, p.215) uses in a case study on automotive design to identify relevant communication channels. The metric represents a **ratio** and is measurable with **medium** effort.

- **Time spend preparing/editing data**

  When there is an awareness of who is the information producer, observer, and user, the standards for sharing the information can be tailored. The improved **communication standards** should represent an optimum regarding the effort for preparing/editing the data between the parties. This lower effort is measurable in time spend on preparing produced data or editing received data. This metric is derived through specific time tracking with **medium** effort and represents an **amount**.

- **Internal customer satisfaction ratio**

  Another metric that can be measured if the information stakeholders' roles are clear is an internal customer satisfaction **ratio**. The customer being the observer/user of the data and the responsible being the producer of the data. This metric is dedicated to measure the **quality of** the **communication**. It can be realized in a lot of ways, depending on the kind of information (raw data, insights, …) and the modus of sharing this information (regularly, occasionally, …). Therefore, the effort to derive this metric **cannot be estimated or specified**.

Improve collaboration

Table 3-16: Overview of derived metrics to measure the improvement in collaboration

Improve collaboration			
Metric	Measured effect	Kind	Effort
Time to solve interdisciplinary issues	Collaboration	Amount	Medium
Number of interface-related recalls	Collaboration	Amount	Small
Common vocabulary in place	Shared understanding	Binary	Medium

- **Time to solve interdisciplinary issues**

  If there is a lack of **collaboration between disciplines**, simple issues tend to consume a lot of time to get settled. Hindering the performance of all involved parties. Measuring the **amount** of time to solve an interdisciplinary issue should reflect this effect and requires a **medium** effort to identify issue occurrence and solution dates.

- **Number of interface-related recalls**

  Another scenario that indicates a lack of **collaboration between disciplines** is that interfaces are not properly aligned. This can lead to a number of interface-related recalls, which is measured with **small** effort in practice and constitutes an **amount**.

- **Common vocabulary in place**

  The use of a shared terminology is key for a good interdisciplinary performance and represents a **shared understanding** of the circumstances. Although it is a **binary** metric, its measurement is complicated and therefore requires **medium** effort. The easiest way to get hold of this metric is by conducting a survey among a reliable target group.

Enable reuse

Table 3-17: Overview of derived metrics to measure the enabling of reuse

Enable reuse			
Metric	Measured effect	Kind	Effort
Time spend on repetitive work	Automation	Amount	Medium
Library in place	Precondition for reuse	Binary	Small
Library usage	Scope of reuse	Amount	Small
Internal customer satisfaction ratio	Artifact reuse case allocation	Ratio	-

- **Time spend on repetitive work**

  Models have the advantage over documents of being highly reusable and most modeling tools include automated document generation. Reducing a lot of standard work, like generating and preparing reports, through **automation and the reuse of models**. This is measured in practice through tracking the **amount** of time spend on repetitive standard work. As this tracking is detailed, this metric requires a **medium** effort.

- **Library in place**

  The more prominent kind of reuse is not concerned with models but with engineering work results, like designed modules, coded functions or design calculations. This binary metric measures if there is a library in place, which is a **precondition for** engineering work artifact **reuse**. This **binary** metric is measured with a **small** effort.

- **Library usage**

  If a library is in place, a more sophisticated metric to quantify the **scope of reuse** is the library usage. In practice it is either measured in the number of users of the library or in the number of artifacts derived from the library. Both representing an **amount**, which is measured with a **small** effort.

- **Internal customer satisfaction ratio**

  If the intended users of the library are known, an internal customer satisfaction can be used to measure the quality of the artifact presentation in the library. Indicating the **usability** of the library and the effort to **allocate** an **artifact** to a **reuse case**. Again, this metric can be realized in a lot of ways, depending on the kind of artifacts and the intended modus of use. Therefore, the effort to derive this metric **cannot be estimated or specified**.

Improve transparency and traceability

Table 3-18: Overview of derived metrics to measure the improvement of transparency and traceability

Improve transparency and traceability			
Metric	Measured effect	Kind	Effort
Number of artifact mappings	Transparency	Amount	Small
Ratio of digital to physical tests	Traceability	Ratio	Small
Formalized change control in place	Transparency	Binary	Small
Number of impacts discovered	Traceability	Amount	Medium
Number of changes covered	Solution robustness	Amount	High

- **Number of artifact mappings**

  Mappings provide context and represent dependencies between artifacts. Knowledge of dependencies increases the **transparency of the correlation of artifacts** for all of the involved. For example, test engineers benefit from a model, mapping requirements to test cases, through the extra context provided. The number of mappings can be measured as an **amount** and with **small** effort.

- **Ratio of digital to physical tests**

  If a model represents the relationships and elements of a system appropriately, they are easily executed in simulations. Therefore, the ratio of tests covered virtually to physically is influenced by a sophisticated use of models. The **ratio** indicates an effect on **model quality and** thereby **traceability**. It is measured with a **small** effort for categorizing test cases.

- **Formalized change control in place**

  The relationships contained in a model allow to identify and analyze the impacts of changes. This supports a formalized change control if it is in place. The **binary** metric measures this with **small** effort and indicates **transparency of** the **change management**.

- **Number of impacts discovered**

  Closely linked to the previous metric, is the determination of the number of unintuitive impacts discovered through traceability analyses. This metric measures the **traceability of changes** in an **amount.** The amount is derived with **medium** effort, as it is complicated to determine a baseline of intuitive impacts. The easiest way would be to question the responsible predicting the impacts before traceability analysis.

- **Number of changes covered**

  As there is an increased traceability in good models, the impact of late changes can be analyzed. Leading to the ability to accommodate changes with low impact relatively late in development. This can also be referred to as **robustness of the solution**. It can be measured through the number of changes that can be covered without influencing resource consumption over a certain threshold. This measurement requires a **high** effort and is captured in an **amount**.

Support the full lifecycle

Table 3-19: Overview of derived metrics to measure support of the full lifecycle

Support the full lifecycle			
Metric	Measured effect	Kind	Effort
Number of ”task forces”	Full lifecycle anticipation	Amount	Small
Internal customer satisfaction ratio	Quality of full lifecycle anticipation	Ratio	-

- **Number of “task forces“**

  Systems Engineering techniques create a holistic understanding covering all lifecycle phases. If these techniques are successfully implemented, problems in later lifecycle phases should decrease and thereby the number of “task forces”. “Task forces” being teams assembled to solve urgent problems quickly. Measuring the **amount** of “task forces” requires a **small** effort and indicates the **anticipation** of the **full lifecycle**.

- **Internal customer satisfaction ratio**

  An internal customer satisfaction ratio can be used to measure the quality of engineering work products in later lifecycle phases. Exemplary customers are the service and maintenance department, manufacturing, and the recycling department. This metric indicates the **quality of full lifecycle anticipation**. As previously stated, this metric can be implemented in a lot of ways, depending on the kind of interaction between lifecycle phases and the covered lifecycle phases. Therefore, the effort to derive this metric **cannot be estimated or specified**.

Foster holistic problem understanding

Table 3-20: Overview of derived metrics to measure the fostering of holistic problem understanding

Foster holistic problem understanding			
Metric	Measured effect	Kind	Effort
Number of plan variants	Holistic problem understanding	Amount	Medium
Degree of requirements fulfillment	Complete problem understanding	Ratio	High
Number of innovations	Depth of problem understanding	Amount	Small
Number of problem-solving iterations	Complete problem understanding	Amount	High
Number of late changes	Complete problem understanding	Amount	Medium
Customer satisfaction	Holistic problem understanding	-	-

- **Number of plan variants**

  As product development is a non-deterministic process, plan variances occur. A **holistic problem understanding** should increase the quality and clarity of planning, decreasing the number of plan variants. This **amount** metric is measured with **medium** effort, as plan variants have to be defined and counted.

- **Degree of requirements fulfillment**

  By developing the system with multiple viewpoints on the problem, the degree of requirements fulfillment should increase. This **ratio** metric requires a **high** measurement effort as different requirements and their fulfillment have to be traded against. If it is measured, it indicates the **completeness of** the **problem understanding**.

- **Number of innovations**

  The change from a component-oriented to a functional-oriented product structure is accompanied by the creation of innovations stemming from an increased **depth of problem understanding.** The **amount** of innovations from functional orientation can be measured with a **small** effort to define and count innovations.

- **Number of problem-solving iterations**

  If there is an **incomplete problem understanding**, it is manifested in a larger number of problem-solving iterations or rework cycles. The measurement of this metric requires a **high** effort, as the **amount** of problem-solving iterations have to be identified in the complex development process.

- **Number of late changes**

  An incomplete problem understanding is usually discovered in later lifecycle phases, when the system design has to be changed to satisfy holistic requirements. Therefore, the **amount** of late changes indicates the **completeness of** the **problem understanding**. It can be measured with **medium** effort after the term late and change are properly defined.

- **Customer satisfaction**

  A **holistic problem understanding** should ultimately lead to an increased customer satisfaction. Customer satisfaction measurement methods and metrics are diverse and depend on the customer, market, and product. Therefore, the effort to derive this metric and its kind **cannot be estimated or specified**.

Table 3-21 summarizes the derived metrics and their attributes to measure MBSE objectives.

Table 3-21: Summary of derived metrics to measure MBSE objectives

Metric	Measured effect	Kind	Effort
Facilitate communication			
Number of users	Scope of sharing knowledge	Amount	Small
Time spend engineering	Value creation	Amount	Medium
Time to find information	Value creation	Amount	High
Ratio of in-house value creation	Change in capacity	Ratio	Small
Ratio of active communication paths	Communication performance	Ratio	Medium
Time spend preparing/editing data	Communication performance	Amount	Medium
Internal customer satisfaction ratio	Quality of communication	Ratio	-
Improve collaboration			
Time to solve interdisciplinary issues	Collaboration	Amount	Medium
Number of interface-related recalls	Collaboration	Amount	Small
Common vocabulary in place	Shared understanding	Binary	Medium
Enable reuse			
Time spend on repetitive work	Automation	Amount	Medium
Library in place	Precondition for reuse	Binary	Small
Library usage	Scope of reuse	Amount	Small
Internal customer satisfaction ratio	Artifact reuse case allocation	Ratio	-
Improve transparency and traceability			
Number of artifact mappings	Transparency	Amount	Small
Ratio of digital to physical tests	Traceability	Ratio	Small
Formalized change control in place	Transparency	Binary	Small
Number of impacts discovered	Traceability	Amount	Medium
Number of changes covered	Solution robustness	Amount	High
Support full lifecycle			
Number of ”task forces”	Full lifecycle anticipation	Amount	Small
Internal customer satisfaction ratio	Quality of full lifecycle anticipation	Ratio	-
Foster holistic problem understanding			
Number of plan variants	Holistic problem understanding	Amount	Medium
Degree of requirements fulfillment	Complete problem understanding	Ratio	High
Number of innovations	Depth of problem understanding	Amount	Small
Number of problem-solving iterations	Complete problem understanding	Amount	High
Number of late changes	Complete problem understanding	Amount	Medium
Customer satisfaction	Holistic problem understanding	-	-

3.4.3 Evaluation of the environment

The development environment derived from literature in section 3.2.3 and visualized in Figure 3-15 was presented to the interview partners. They were asked if the environment accordingly represents their work environment to reflect the elements that might be affected by a transformation toward MBSE.

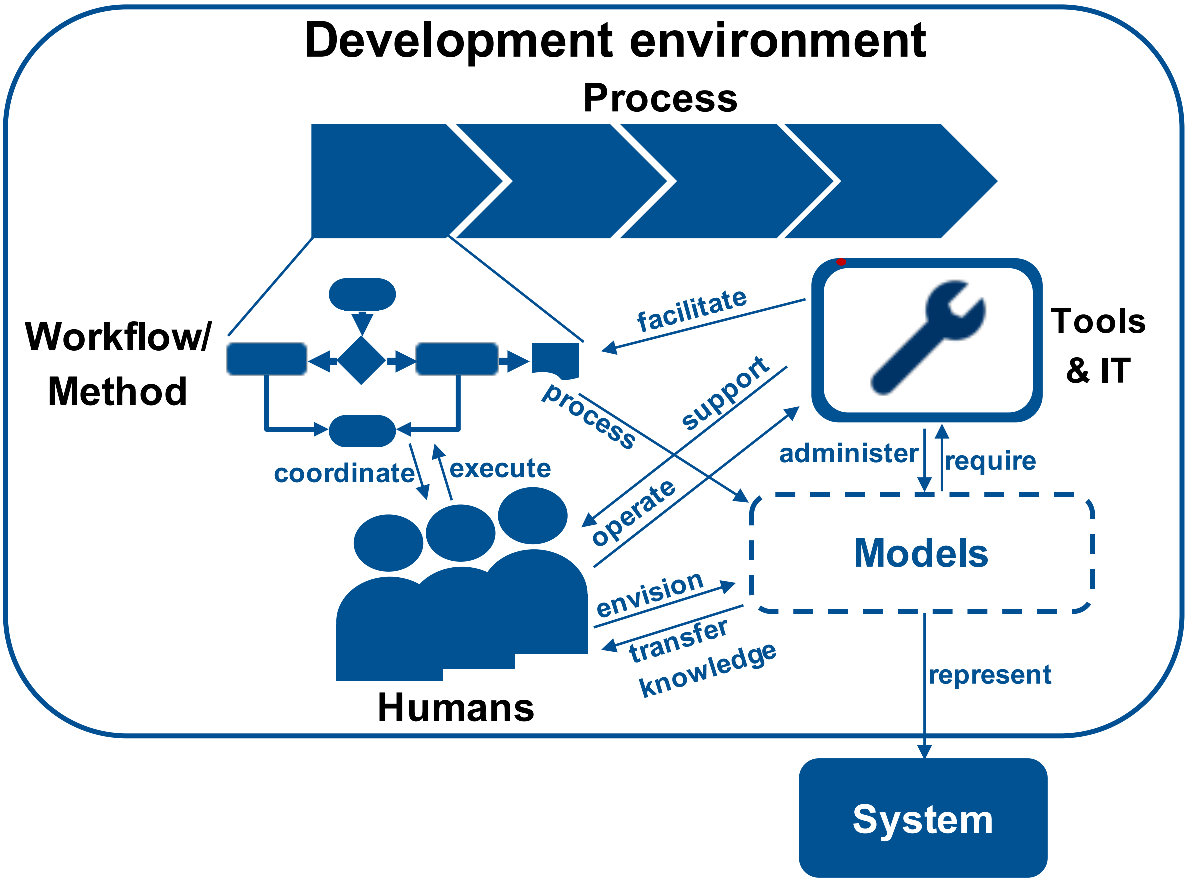

Figure 3-15: Structure of the development environment

All of the consulted experts confirmed that the environment sufficiently reflects their work environment and contains the elements that might change in an MBSE transformation. On top of that two experts had already drawn up a similar graphics for their development environment. The purpose of this graphic is in designing the new process and IT systems as well as educating colleagues. It should be highlighted, that both graphics were almost entirely transferable to other companies. The only thing limiting the transferability was company-specific wordings.

Out of this observation can be deduced that an **overview of the development environment as subject to change is necessary** and that the **environment presented in this thesis accordingly represents such an overview**.

3.4.4 Changes in the environment

After the structure of the development environment has been evaluated, as described in the previous section, the interview partners were asked which of the elements and relationships of the environment are subject and most likely to change in a transformation towards MBSE.

80 % of participants **stated that all elements** of the environment **are subject to change** and that none of them is out of scope. Participants who stated that not all elements are in scope did so because they believe that the high-level development process will not be changed or only its milestones might be changed. Leaving out a change in the process steps or their order.

30 % of interview partners emphasized on the **human**, who according to them is the **most important element to be changed and also the hardest**. They justified the importance through the key position of the human. If the transformation should prevail, the mindset of the human has to change. Changing this mindset is seen as particularly hard. The willingness to change it has to be achieved in a step by step approach, demonstrating positive results and simplifying the human efforts.

The anticipated and observed changes are listed according to the respective elements below:

Process

Most participants were in consensus, that the milestones of the process change, but hesitated on the process steps. At last, most participants agreed that the steps themselves and their order is changed. One participant mentioned that the character of the process will change as well. Meaning that the push of information from the early to the later phases will be replaced by an information pull. Leading to a more service-oriented process. A point all participants agreed on is that MBSE will have positive consequences on cycle time, level of integration, interactivity, and flexibility of the process. As mentioned before, 20 % of interview partners believe that the high-level development process will not change.

Workflow/Method

Workflows and methods will change towards the usage of models and systems engineering techniques. There were different opinions on how strictly the workflow and the methods should be predetermined. As of today, workflow and selection of methods is flexible in earlier development phases and gets stricter in later phases. Some participants would like to prescribe the methods to use in early development in a standardized workflow. Others want to broaden the selection of methods through providing training in systems engineering and models. At this point, none has proofed as the superior approach.

Tools/IT

All tools and IT systems are supposed to be further integrated. Therefore, most participants argued that significant effort will be on the transformation of this element. Special focus will be on the integration of different modelling tools, which resulted from uncoordinated digitization activities of several departments. In most companies, the IT department is not the same as the development department, making a successful transformation complicated.

Humans

As described above, the human is the hardest but most important element to change. The further emphasis on models and thereby tools will pose new requirements on humans. They have to be educated and train to obtain the knowledge and skills needed to operate them. Some experts observed a change in focus of humans, as they observed an increasing number of generalists compared to specialists with the allocation of new work packages and the increase of explicit knowledge. That’s why they suppose that a modification of incentives and the mindset is necessary. Also, new roles should be introduced to the team, like an MBSE method responsible.

Models

Models or more precise the model landscape used, has to be fast, efficient and effective to prevail in practice. As most participants stated, their company’s patchwork model landscapes are currently not up to that challenge. Another challenge that still has to be overcome is the anxiety of the new, which often strikes when new models are introduced.

3.5 Summary

The insights obtained in the literature studies, survey and expert interviews are briefly recapitulated to form the knowledge base for the introduction of the guideline in the next chapter.

Literature studies

Three insights have been obtained through literature studies. First, there is a unified understanding in the model-based systems engineering community, that complexity drives the adoption of MBSE. Second, six general MBSE capabilities: facilitate communication, improve collaboration, enable reuse, improve transparency and traceability, support the full lifecycle, and fostering a holistic problem understanding have been derived. Third, a development environment consisting of process, workflow/method, tools/IT, humans, models, and their relationships, covering necessary changes to become an MBSE environment has been depicted.

Survey

The survey conducted in a semi-experienced and heterogenous population contributed several insights to the state of practice, MBSE potential estimation, excellence improvement identification, influence on the environment structure and transformation approach exploration.

Regarding the state of practice, a potential of growth has been diagnosed in two interpretations. An identified key challenge for the participants is the implementation of MBSE, as there is a perceived lack of guidelines on this.

The participants share the assumption from literature that complexity is the main driver for MBSE. After three kinds of complexity (organizational, product, and inertia) have been identified in a principal components analysis and cumulated in a total complexity measure, this assumption has been positively tested.

Regarding excellence improvements, a correlation between emphasis on facilitating communication and improving collaboration has been identified. Generally, a high number of emphases should be avoided, as it increases the ambiguity of the MBSE concept and different claims about what MBSE is first become evident during implementation.

Several correlations between prioritizations of development environment elements in the MBSE transformation have been identified. The influence of emphasized MBSE capabilities on the prioritization of the environment elements has also been examined and showed significant effects.

Last, the answers regarding integration of models and the scope of the transformation approach have been analyzed. Tying existing models together is inevitable for emphasis on some MBSE capabilities but is problematic in combination with a high number of emphasized capabilities. The model credibility of the legacy models, assumptions used to tie existing models together, and the definition of the scope as well as the purpose understanding of the models to be should be reviewed before committing to a modeling approach. The evaluation of approaches should become a standard practice. The scope of the transformation approach influences the model qualities model credibility, verifiable, and well-formed for optimization.

Expert interviews

Expert interviews confirmed and authenticated the development environment derived from literature and the identified MBSE capabilities. Furthermore, metrics measuring the success of the MBSE transformation were identified and mapped to the MBSE capabilities. Regarding changes in the development environment, the human was highlighted as key figure and opposing to organizational aspects in the survey, 20 % of experts stated that the high-level development process is out of scope in the transformation.

The insights shaping the guideline are cumulated in the guideline, which is introduced in the next chapter.

4 Guideline cycle

This chapter describes a cycle through the guideline for the implementation of MBSE in existing product development environments. The full guideline is depicted in Figure 4-1.

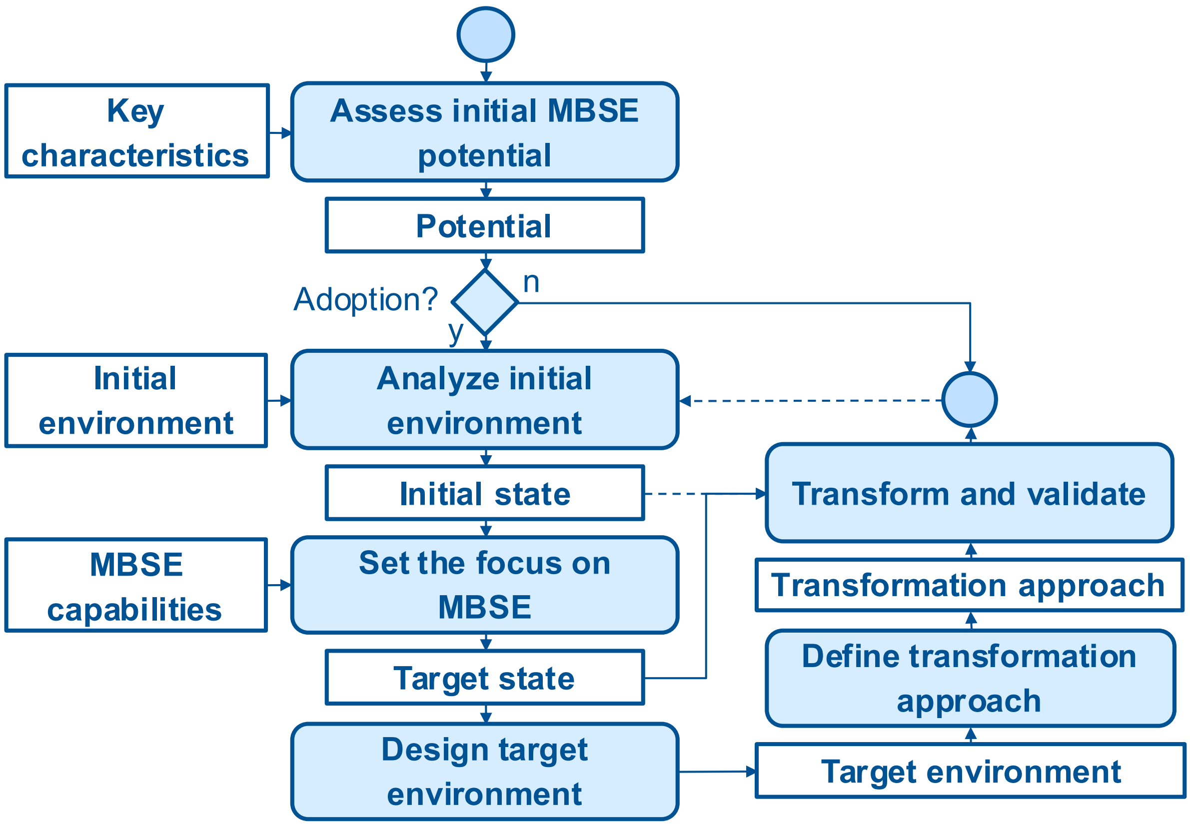

Figure 4-1: Proposed guideline for the implementation of MBSE

The guideline cumulates insights gained in the last chapter and interrelates the research objectives. First, key characteristics are used to assess the initial MBSE potential in an organization. Leading up to a decision about the adoption of MBSE. If MBSE is adopted, the initial environment is analyzed to quantify the initial state. Using the results of the analysis, the focus on MBSE capabilities is set in the next step and the target state is elaborated. Using the target state, a suitable target environment is designed in the proceeding step. Furthermore, a transformation approach is defined to realize the target environment. Finally, the transformation is carried out and its success is continuously validated in a control loop.

The six steps of the guideline are further described in the following subchapters. In the next chapter, the guideline will be demonstrated and verified on a practice-inspired case study.

4.1 Assess initial MBSE potential

The guideline starts with the assessment of the initial MBSE potential in an organization. As visualized in Figure 4-2, key characteristics are used to assess the initial MBSE potential in an organization. Leading up to a decision about the adoption of MBSE.

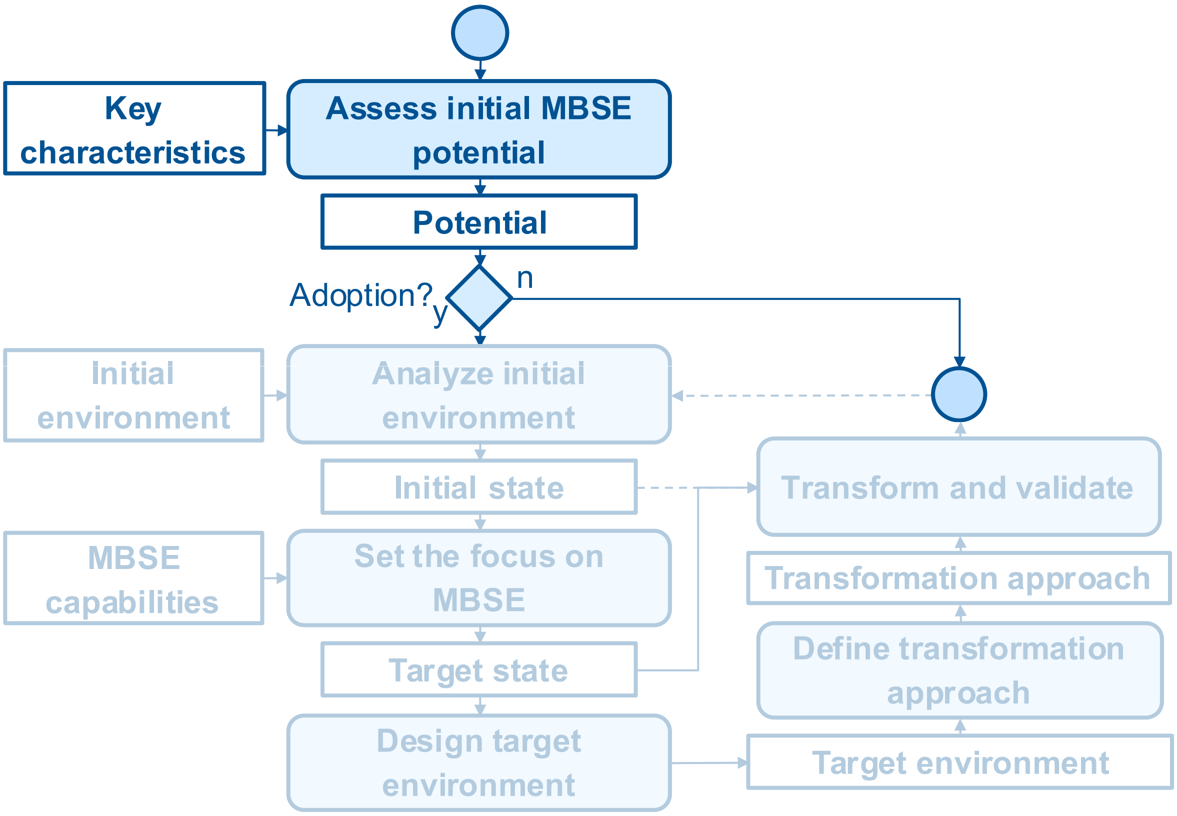

Figure 4-2: Guideline step one "assess initial MBSE potential"

The key characteristics of an organization's product and development tasked have been elaborated in an expert discussion at the Massachusetts Institute of Technology. They are categorized according to Table 4-1.

Table 4-1: Values for the characteristics to be used in the calculation of the component scores

j	Value for characteristic	1	2	3	4	5	6	7	8
1	Number of contractors/suppliers	0	1	1 - 5	5 - 20	20 - 50	50 - 100	100 - 1.000	> 1.000
2	Number of employees	1 - 10	10 - 50	50 - 100	100 - 500	500 - 1.000	> 1.000	-	-
3	Number of changes	0	1	1 - 5	5 - 10	10 - 20	20 - 100	> 100	-
4	Number of disciplines	1	1 - 5	5 - 10	10 - 20	20 - 30	30 - 50	> 50	-
5	Part count	0	1 - 10	10 - 100	100 - 1.000	1.000 - 10.000	10.000 - 100.000	100.000 - 1.000.000	> 1.000.000
6	Unit cost in $	1 - 100	100 - 1.000	1.000 - 10.000	10.000 - 100.000	100.000 - 1.000.000	1.000.000 - 10.000.000	> 10.000.000	-
7	Source lines of code	0	1 - 10	10 - 100	100 - 1.000	1.000 - 10.000	10.000 - 100.000	100.000 - 1.000.000	> 1.000.000
8	Cycle time	< 1	1 - 6	6 - 18	18 - 36	36 - 60	60 - 120	> 120	-

These values are then used to calculate the three specific components respectively inertia, organizational-, and product-related complexity using formula 4.1.

$$Component\ score_i = \sum_{j=1}^{8} Component\ score\ coefficient_{ij} \times \frac{(Characteristc_j - \mu_j)}{\sigma_j} \qquad (4.1)$$

The specific mean (μ) and standard deviation (σ) can be read from Table 4-2.

Table 4-2: Specific mean and standard deviation for each characteristic

j	Variable	μ_j	σ_j
1	Number of contractors/suppliers	4,82	1,673
2	Number of employees	3,70	1,584
3	Number of changes	4,53	1,496
4	Number of disciplines	4,09	1,504
5	Part count	5,14	1,633
6	Unit cost in $	4,93	1,787
7	Source lines of code	5,91	1,882
8	Cycle time	4,43	1,448

All three complexities are then combined in formula 4.2 to form a measure for the complexity the organization is exposed to.

$$Total\ complexity = \sum_{i=1}^{3} Component\ score_i \quad (4.2)$$

As was shown in section 3.2.1 and 3.3.3, the assumption that the prevailing complexity is proportional to the potential achievable through MBSE is a common and valid assumption. Therefore, the total complexity is used as crucial information for a management decision if MBSE should be adopted or not. The total complexity can be compared to the total complexity scores of different industries in Figure 3-10. If MBSE is adopted, the next step of the guideline is carried out. If not, the guideline ends.

4.2 Analyze initial environment

After there is a consensus that MBSE should be adopted, the initial environment is analyzed to quantify the initial state, as visualized in Figure 4-3.

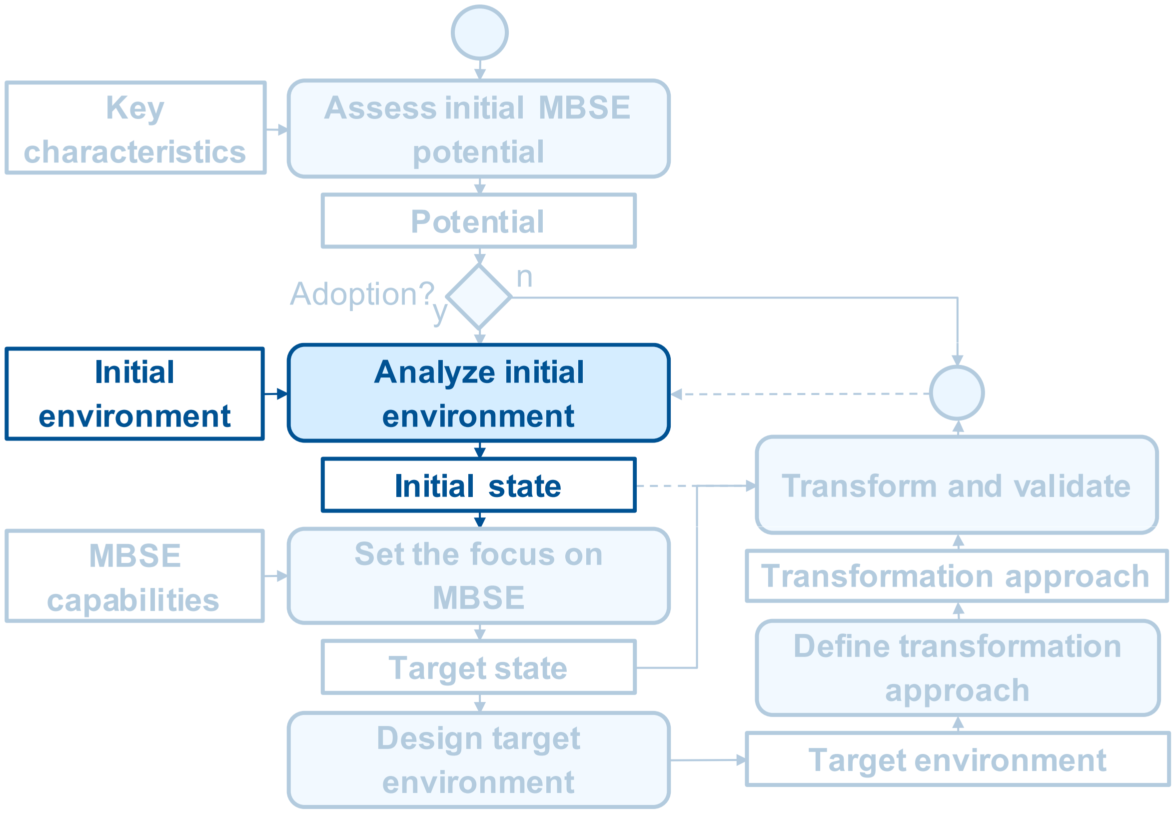

Figure 4-3: Guideline step two "analyze initial environment"

To analyze the initial environment, the organization-specific instantiation of the environment has to be matched to the development environment structure derived in section 3.2.3 and visualized in Figure 4-4.

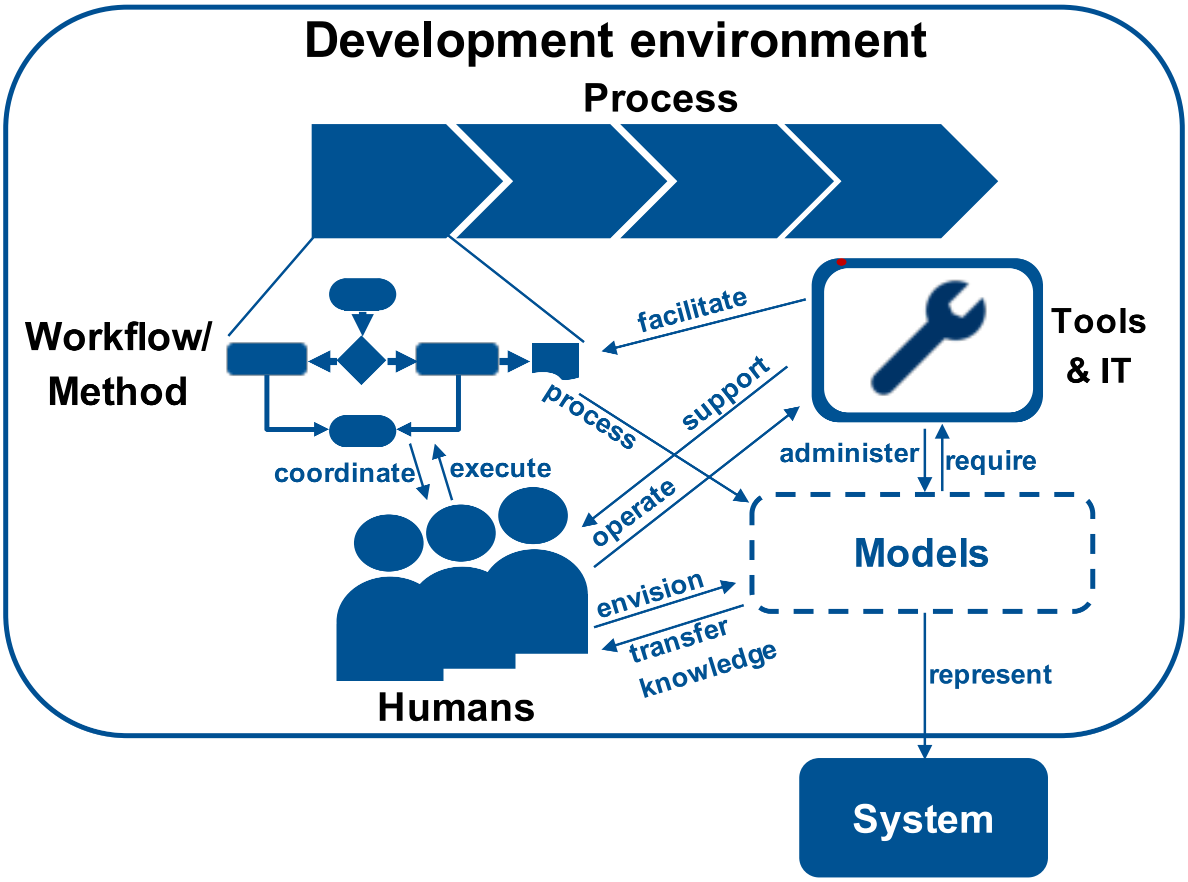

Figure 4-4: Structure of the development environment

After the organization-specific environment was outlined, shortcomings or improvement potentials should be documented as concrete as possible, forming the initial state. To be precise regarding the initial state, metrics like the exemplary ones derived from the expert interviews in section 3.4.2 should be used. They should indicate the current shortcomings but should also be able to depict possible improvements achieved through MBSE. The organization-specific development environment structure with its initialized elements and relationships helps in identifying these metrics for a specific organization.

4.3 Set the focus on MBSE

As the initial state is adequately described, it is used as one of two inputs to setting the focus regarding MBSE capabilities. The second input, shown in Figure 4-5, are the MBSE capabilities, as generalized in section 3.2.2.

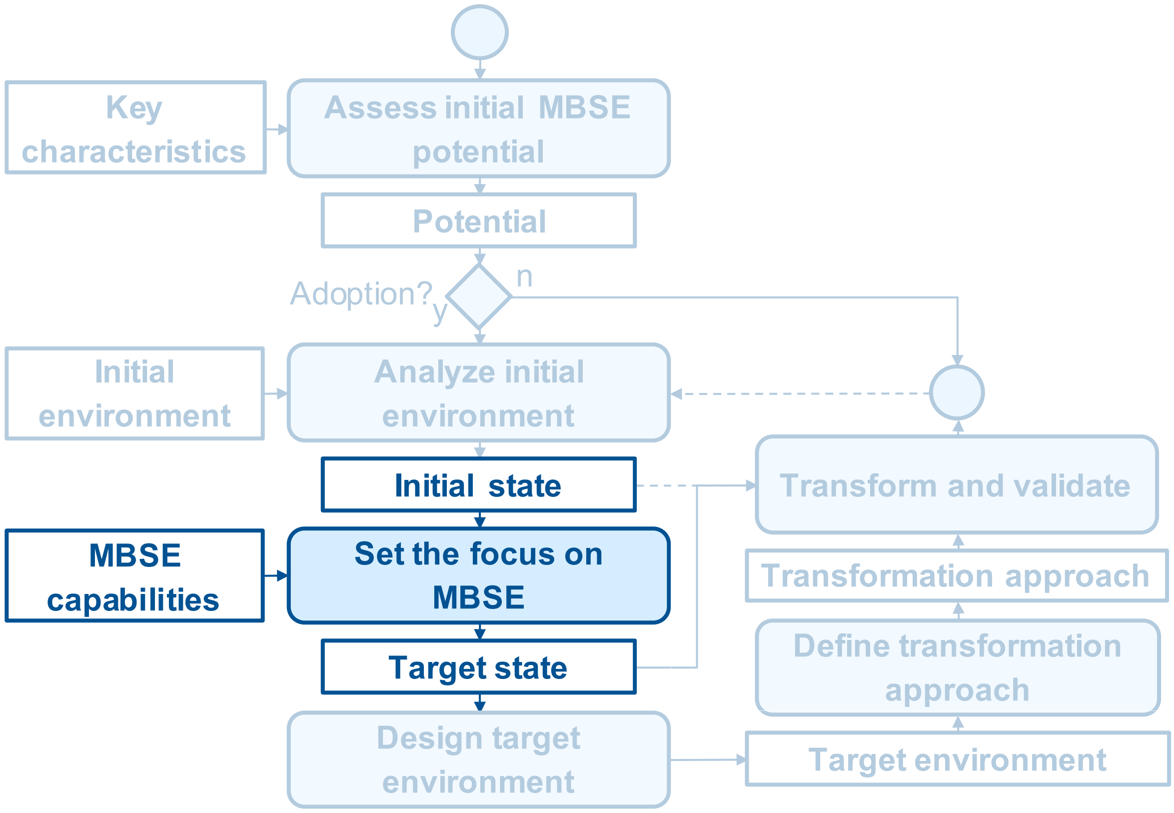

Figure 4-5: Guideline step three "set the focus on MBSE"

The six identified MBSE capabilities are facilitate communication, improve collaboration, enable reuse, improve transparency and traceability, support full lifecycle, and foster holistic problem understanding. It is necessary to set a focus on the capabilities suiting the initial state and not try to achieve all with even effort, as it increases the ambiguity of the MBSE concept and different claims about what MBSE is do not become evident after the implementation started. To set a focus, it is proposed to rank the emphasis on the capabilities and if possible, exclude some of them as done by the participants of the survey and evaluated in section 3.3.3. The ranking forms the minimal viable target state. Using the ranking of emphasis on MBSE capabilities, the target state should be further described. This means that the metrics describing the initial state, which are affected by the focused MBSE capabilities should be identified. Furthermore, the effects on these metrics should either be anticipated trend-wise or even in the form of targets.

4.4 Design target environment

After the target state has been worked out in the previous step, it is used in this step to design the target environment as indicated in Figure 4-6.

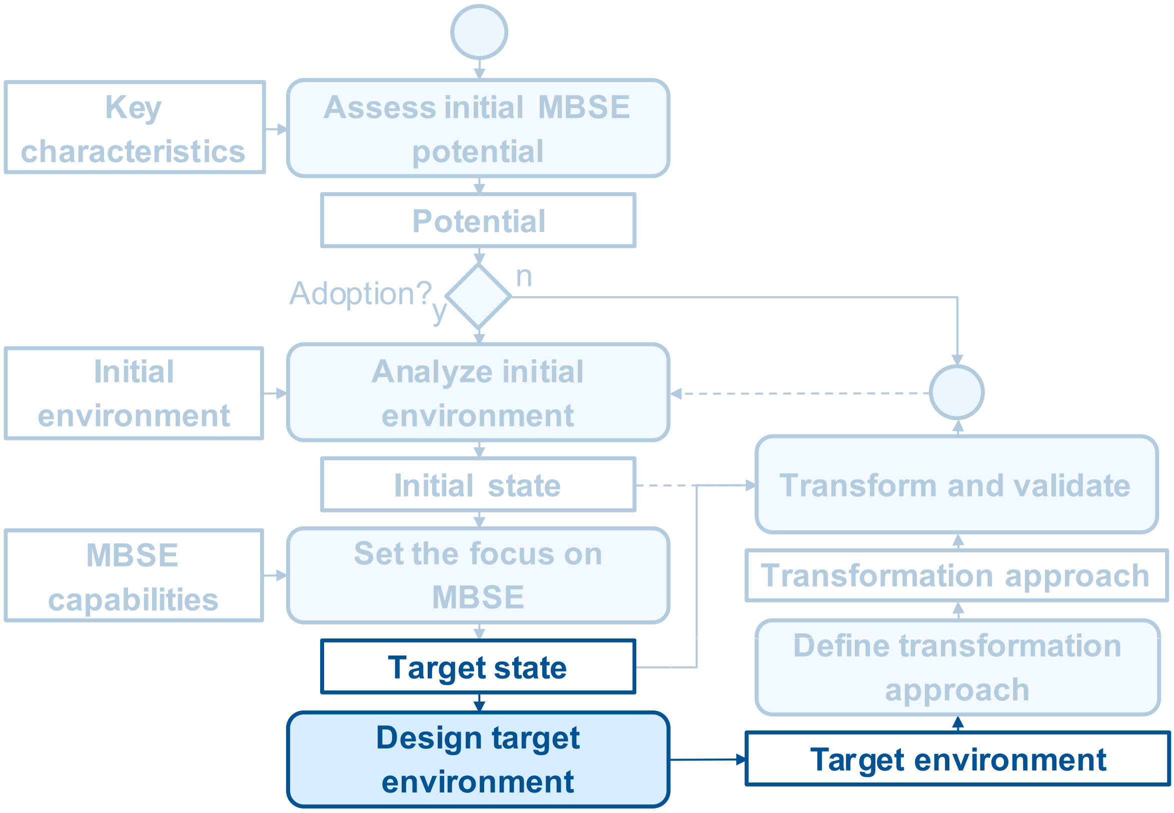

Figure 4-6: Guideline step four "design target environment"

Therefore, the target state is used to design and reshape the initial development environment towards a target development environment. To do so, the correlations between emphasis on MBSE capabilities and prioritizations of the transformation of certain development environment elements derived in section 3.3.3 and recapitulated here can be used for orientation.

- high emphasis on improving collaboration significantly increases the priority of models and methods, while significantly decreasing the priority of organizational culture
- high emphasis on reusing architecture and engineering work results significantly increases the priority of organizational culture, while significantly decreasing the priority of software tools
- high emphasis on improving transparency and traceability significantly increases the priority of organizational structure, while significantly decreasing the priority of methods and models
- high emphasis on improving later lifecycle activities significantly increases the priority of process and workflows

Other observations from the survey data that are necessary for the design of a target environment are the three, identified correlations between prioritizations found in the same section.

- Increased priority on transforming methods and models increases the priority on transforming process and workflows
- Increased priority on transforming methods and models also increases the priority on transforming software tools
- Increased priority on transforming organizational culture increases the priority on transforming organizational structure

More important than sticking to these observations is that a target environment is found which all stakeholders can agree upon and that considers consequences on all elements and relationships of the development environment.

4.5 Define transformation approach

Coming from the target environment, the transformation approach is defined, as shown in Figure 4-7.

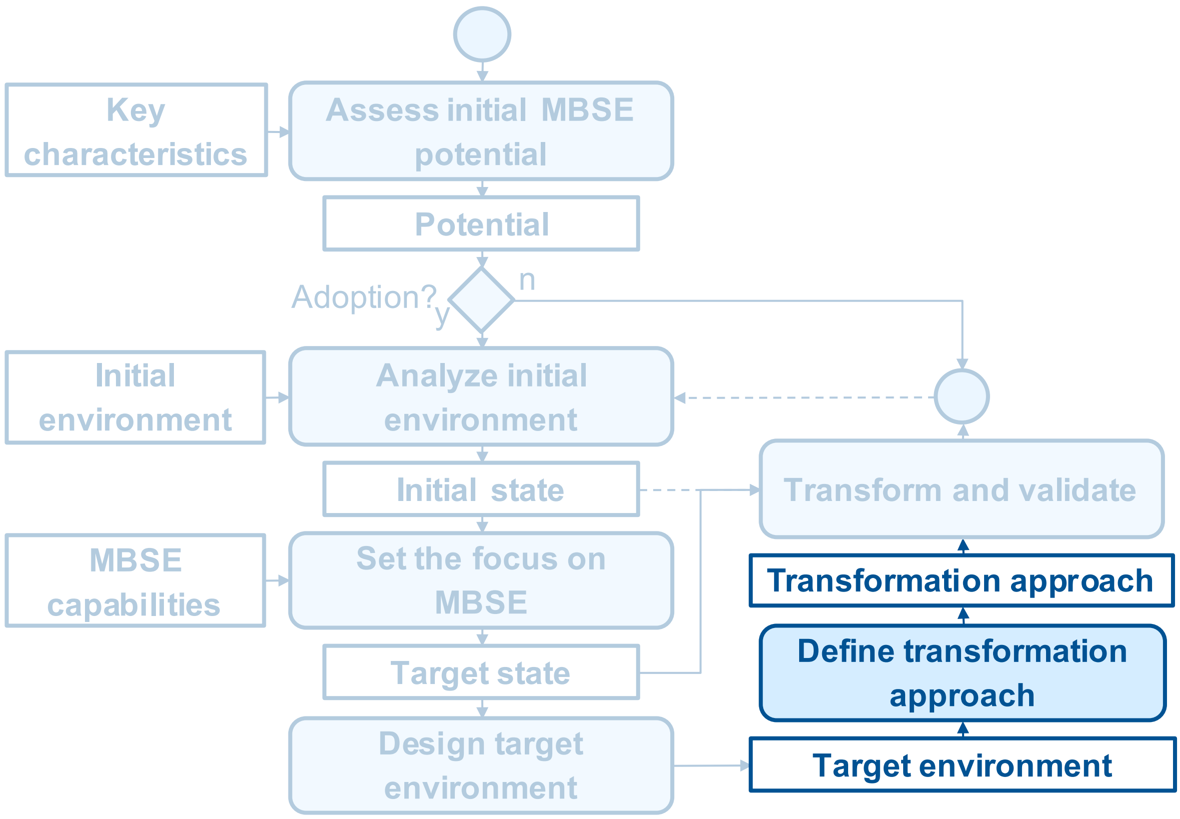

Figure 4-7: Guideline step five "define transformation approach"

To define the transformation approach, two major attributes of the approach have been examined in the survey in section 3.3.3. The approach to modeling and the adoption scope.

First, tying existing models together is inevitable for emphasis on reusing architecture and engineering work results as well as improving problem understanding. These tow capabilities built up on the knowledge captured in existing models. Nonetheless, it should be considered that tying existing models together exposes more constraints on the overall transformation approach as clean sheet modeling. On top of that, the model credibility of the legacy models, assumptions used to tie existing models together, and the definition of the scope as well as the purpose understanding of the models to be should be reviewed before committing to a modeling approach.

The scope of the transformation approach mainly influences the model qualities model credibility, verifiable, and well-formed for optimization. A project-wide adoption scope has negative effects on model credibility and models being well-formed for optimization. If these model qualities are crucial, another scope of the adoption should be emphasized, or counter measures should be in place. The difficulties in verifying models increases with the extent of the models and thereby with the scope of the adoption. The extent of the model and how it can be verified should be closely monitored in organization-wide adoptions.

On top of these two major attributes which have to be determined, the target environment should be used to inform all stakeholders and foster a positive mindset towards the transformation effort. Whatever the final approach ends in, it should be evaluated by different disciplines in-house.

4.6 Transform and validate

In the final step of the guideline, the transformation approach is carried out and validated in a validation loop depicted in Figure 4-8.

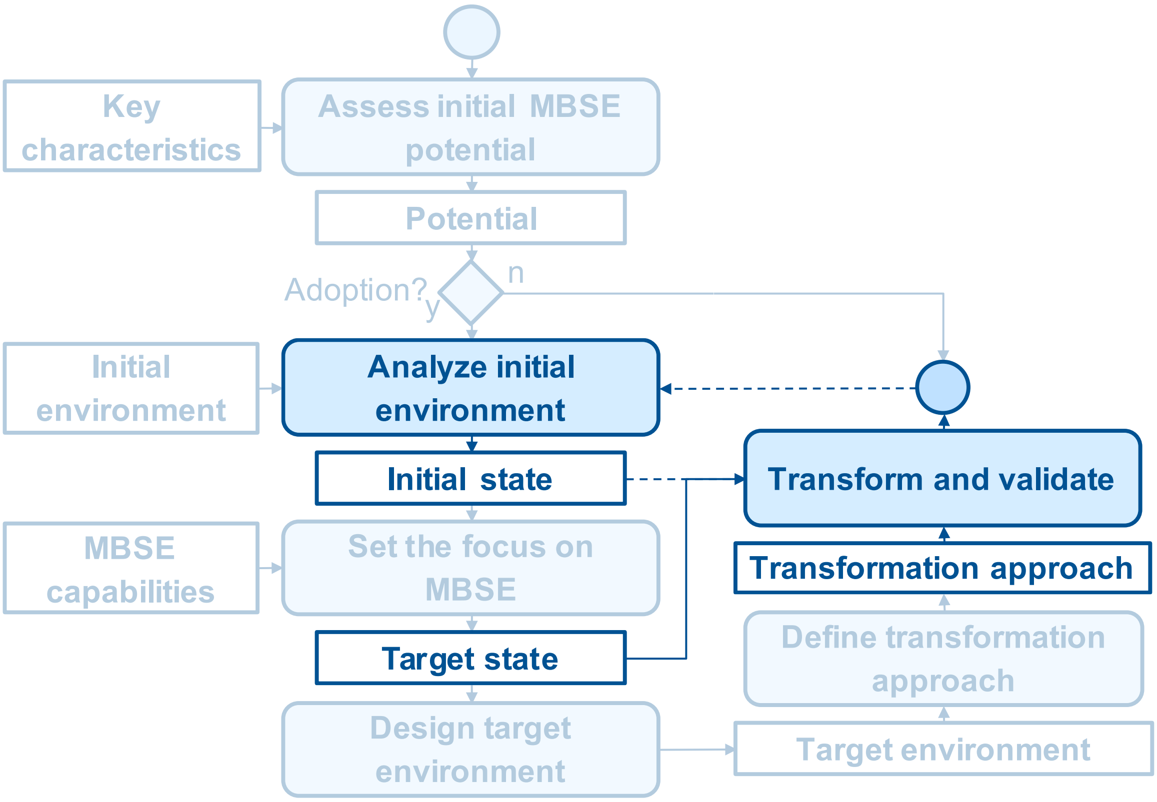

Figure 4-8: Guideline step six "transform and validate"

The transformation is executed while the convergence of current to target state is closely monitored. Therefore, the metrics defined to assess the initial state and making up the target state are monitored in the development environment in predefined cycles. The explanatory power of the metrics should allow the transformation responsible to steer the transformation and demonstrate its success. Demonstrating the success is not only necessary to justify efforts undertaken but also to motivate further efforts.

4.7 Summary

The created guideline for the implementation of MBSE in existing product development environments consist of six steps, described in this chapter. After the initial assessment of MBSE potential, the adoption of MBSE is decided upon. Following a positive decision, the initial environment is analyzed and a focus on MBSE capabilities is set. The target state and environment are elaborated in the succeeding steps. Leading to the built-up of a transformation approach, which is applied and managed in a validation loop.

The guideline was created to enable the meaningful and successful adoption of MBSE in existing product development environments. How the guideline handles a practice-inspired case study is demonstrated in the next chapter.

5 Verification and validation

This chapter concerns the verification and validation of the created guideline for the implementation of MBSE. It is divided in two parts.

The first part demonstrates the application of the guideline on a practice-inspired case study to verify that the solution statement provides the desired functionality. According to Blessing and Chakrabarti (2009, p.184) this verification is called a *"support evaluation"*.

The second part focuses on assessing the usability of the solution regarding predefined criteria. Blessing and Chakrabarti (2009, p.184) call this an *"application evaluation"*. The predefined criteria used for this validation are the requirements defined in subchapter 1.2.

The third validation mentioned by Blessing and Chakrabarti (2009, p.185) the *"success evaluation"*, evaluating the provided value of the solution, is not part of this thesis. As Blessing and Chakrabarti (2009) in Biedermann et al. (2013, p.50) argue, this kind of validation should not be carried out by the developer of the solution, as his familiarity with the solution might negatively impact the validation. The next section covers the support evaluation on a practice-inspired case study.

5.1 Verification

Before the support evaluation focuses on the practice-inspired case study, it should be mentioned that the MBSE capabilities and the development environment structure have been subject to a support evaluation through the expert interviews described in subchapter 3.4. Therefore, this subchapter will solely focus on the evaluation and thereby verification of the guideline. The case-study used to verify the guideline is based on practice but does not reflect the results of a real industrial case study. To structure this subchapter, first the initial situation at the fictive organization is described. Second, the guideline is applied to the organization. And in the third section the verification is summarized.

Initial situation

A head of development at an automotive original equipment manufacturer (OEM), has heard of MBSE streamlining development activities in the aerospace industry. He is generally open to the idea of adopting MBSE and would like to assess as well as potentially implement MBSE in his organization.

Application of the guideline

The application of the guideline is structured in the six phases of the guideline. Starting with the assessment of the initial MBSE potential.

Assess initial MBSE potential

To assess the initial MBSE potential, the characteristics of a car and the automotive development task are used to obtain the necessary values to calculate the complexities.

Table 5-1 shows the values for the characteristics for an automotive OEM.

Table 5-1: Values for the characteristics of an automotive OEM

j	Value for characteristic	1	2	3	4	5	6	7	8
1	Number of contractors/suppliers	0	1	1 - 5	5 - 20	20 - 50	50 - 100	100 - 1.000	> 1.000
2	Number of employees	1 - 10	10 - 50	50 - 100	100 - 500	500 - 1.000	> 1.000	-	-
3	Number of changes	0	1	1 - 5	5 - 10	10 - 20	20 - 100	> 100	-
4	Number of disciplines	1	1 - 5	5 - 10	10 - 20	20 - 30	30 - 50	> 50	-
5	Part count	0	1 - 10	10 - 100	100 - 1.000	1.000 - 10.000	10.000 - 100.000	100.000 - 1.000.000	> 1.000.000
6	Unit cost in $	1 - 100	100 - 1.000	1.000 - 10.000	10.000 - 100.000	100.000 - 1.000.000	1.000.000 - 10.000.000	> 10.000.000	-
7	Source lines of code	0	1 - 10	10 - 100	100 - 1.000	1.000 - 10.000	10.000 - 100.000	100.000 - 1.000.000	> 1.000.000
8	Cycle time	< 1	1 - 6	6 - 18	18 - 36	36 - 60	60 - 120	> 120	-

Table 5-2: Mean and standard deviation for each variable

j	Variable	μ_j	σ_j
1	Number of contractors/suppliers	4,82	1,673
2	Number of employees	3,70	1,584
3	Number of changes	4,53	1,496
4	Number of disciplines	4,09	1,504
5	Part count	5,14	1,633
6	Unit cost in $	4,93	1,787
7	Source lines of code	5,91	1,882
8	Cycle time	4,43	1,448

Using these characteristic values and the statistics from Table 5-2 in formula 4.1 results in the values for the specific complexities. The calculation is demonstrated for the organizational complexity.

$$\begin{aligned} Organizational\ complexity \\ &= 0{,}311\left(\frac{6-4{,}82}{1{,}673}\right) + 0{,}265\left(\frac{5-3{,}70}{1{,}584}\right) + 0{,}276\left(\frac{6-4{,}53}{1{,}496}\right) \\ &+ 0{,}199\left(\frac{5-4{,}09}{1{,}504}\right) + 0{,}159\left(\frac{6-5{,}14}{1{,}633}\right) - 0{,}117\left(\frac{4-4{,}93}{1{,}787}\right) \\ &+ 0{,}083\left(\frac{7-5{,}91}{1{,}882}\right) - 0{,}004\left(\frac{5-4{,}43}{1{,}448}\right) = 1{,}02 \end{aligned}$$

$$Product-related\ complexity = -0{,}09$$

$$Target-related\ complexity = 0{,}00$$

The specific complexities reveal a high organizational complexity, while product-related complexity and inertia are normal compared to other organizations of the survey population. The total complexity is calculated using formula 4.2.

$$Total\ complexity = 1{,}02 - 0{,}09 + 0{,}00 = 0{,}93$$

The total complexity, driven by the organizational complexity, is generally high compared to other organizations of the survey population (see Figure 3-10). Therefore, the head of development decides to adopt MBSE.

Analyze initial environment

To start off the adoption of MBSE, the current development environment of the organization is analyzed. Therefore, the generic development environment structure from section 3.2.3 is used. Figure 5-1 shows the instantiation of the environment for the management of requirements in the process step concept development at an automotive OEM.

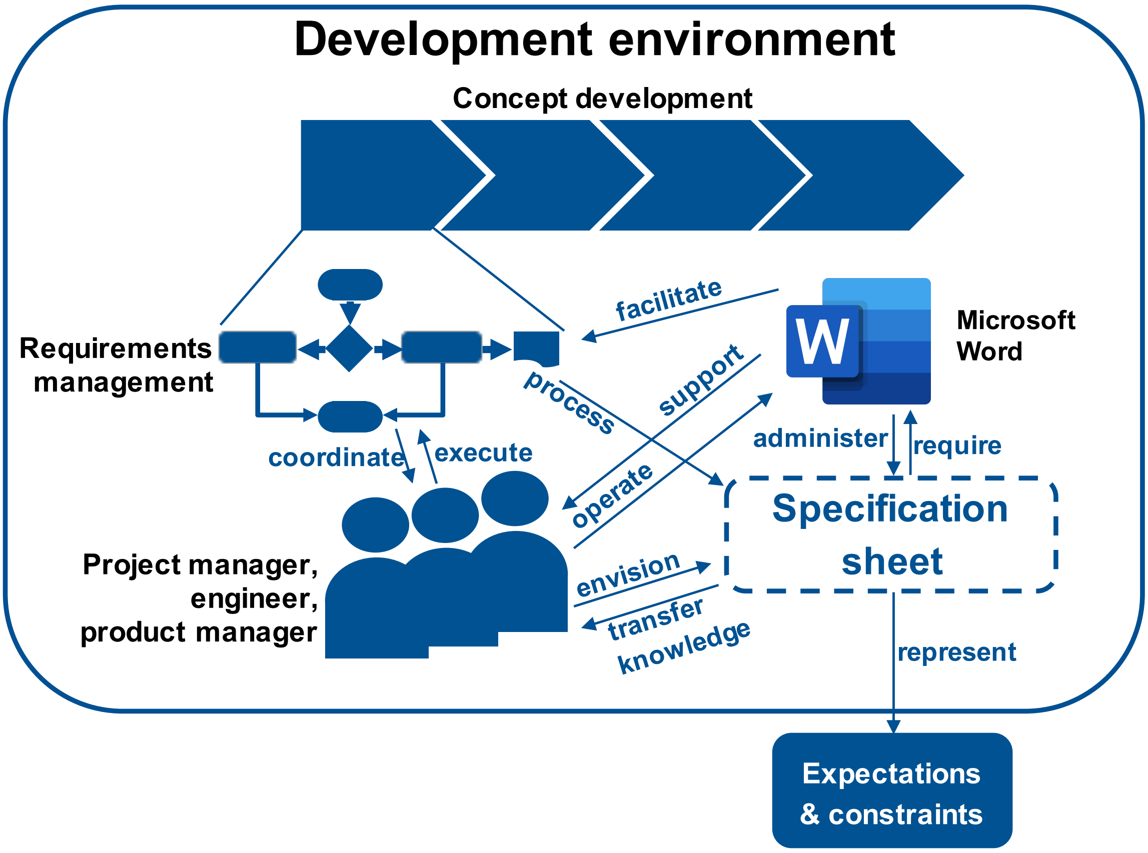

Figure 5-1: Initial instantiation of the development environment for the management of requirements during concept development at an automotive OEM

Currently, all project stakeholders individually contribute requirements specifying attributes of the car to be developed into a specification sheet. The digital specification sheet cataloguing requirements is a document created and edited in Microsoft Word.

The requirements are desired to meet the expectations of the customer and satisfy internal as well as external constraints. For example, an engine has to meet a certain level of power expected by the customer, should reuse existing parts, and should fulfill all emission laws. After all stakeholders have contributed their requirements, a multidisciplinary committee of responsible project managers, engineers, and product managers agrees on a version of the specification sheet. This version is distributed to all departments, so that they can start developing.

After some time, changes to the requirements occur. The reasons for these can be externally, like new emission laws or internally, like decreasing cross sections through an alternative design. The change is brought to the attention of the committee, which meets to evaluate the impact of the change and to cover the changed requirements in a new version of the specification sheet. This specification sheet is again distributed between the development departments.

As general changes (20-100/development project) and thereby changes to requirements happen often, negative aspects of this practice have caught the attention of the head of development.

First, quite often departments do not use the latest released specification sheet. As they tend to start developing on the information of the first specification sheet and do not check for updates. This causes unnecessary rework to meet under fulfilled requirements or leads to unnecessary over fulfilled requirements. Also, the currently valid version is not easily identifiable for the individual developer.

Second, the process from the identification of a change, to the distribution of an updated specification sheet is lengthy. Leading to a large amount of time and effort spend on meeting already outdated requirements.

The head of development uses these negative aspects of the current development environment to define metrics assessing the initial state. Looking at the metrics identified in section 3.4.2, the time spend to find information for the individual engineer and the time spend by the committee preparing the requirements could be used to assess the initial state and indicate the improvement through MBSE. But the head of development decides to use the better suiting metrics number of distributed specification sheet versions and the latency time between a discovered change and a newly distributed specification sheet. For the initial state the values of these metrics are multiple (n) for the number of versions and one week for the latency time.

Set the focus on MBSE

Using the identified shortcomings substantiated through the values of the metrics, the head of development sets a focus on MBSE capabilities. As he is most concerned with the current communication, he emphasizes facilitating communication the most. As he saw that other organizations emphasizing highly on facilitating communication also emphasize high on improving collaboration (see section 3.3.3), he makes that the second emphasis. After these two emphases have been identified, he envisions the target state. The target state being only one distributed and therefore used source of information and a latency time from identified change to updated and distributed information of one day.

Design target environment

Following the emphasis on capabilities and definition of a target sate, the target environment is designed. Therefore, the head of development seeks orientation from the correlations between the capabilities emphasized by him and the prioritizations of the transformation of environment elements by other organizations, depicted in section 3.3.3.

The first emphasis of facilitating communication has no significant correlations with the prioritizations. However, improving collaboration significantly increases the priority of models and methods, while significantly decreasing the priority of organizational culture in the transformation towards MBSE. Therefore, the head of development evaluates other model alternatives to the specification sheet. He is convinced by the capability of object models, which allow for defining hierarchies within requirements and their sources. Enabling change impact analysis. As object models cannot be represented in Microsoft Word, a new tool, namely IBM Rational Doors, has to be acquired.

Other effects of the change of the model are humans have to be enabled to use the model and tool, the new model has to be incorporated into the existing workflow and process. To cope with these effects, the head of development decides to train one employee per department in the use of object models as well as the new tool. Thereby, a responsible keeping track with the requirements changes in the sole information source, the object model of requirements, is determined. Also, the workflow to update and distribute the information impacted by a change in requirements is fundamentally changed to meet the desired latency time. These fundamental changes are mostly covered by time savings achieved through using impact analyses. The resulting target environment is depicted in Figure 5-2.

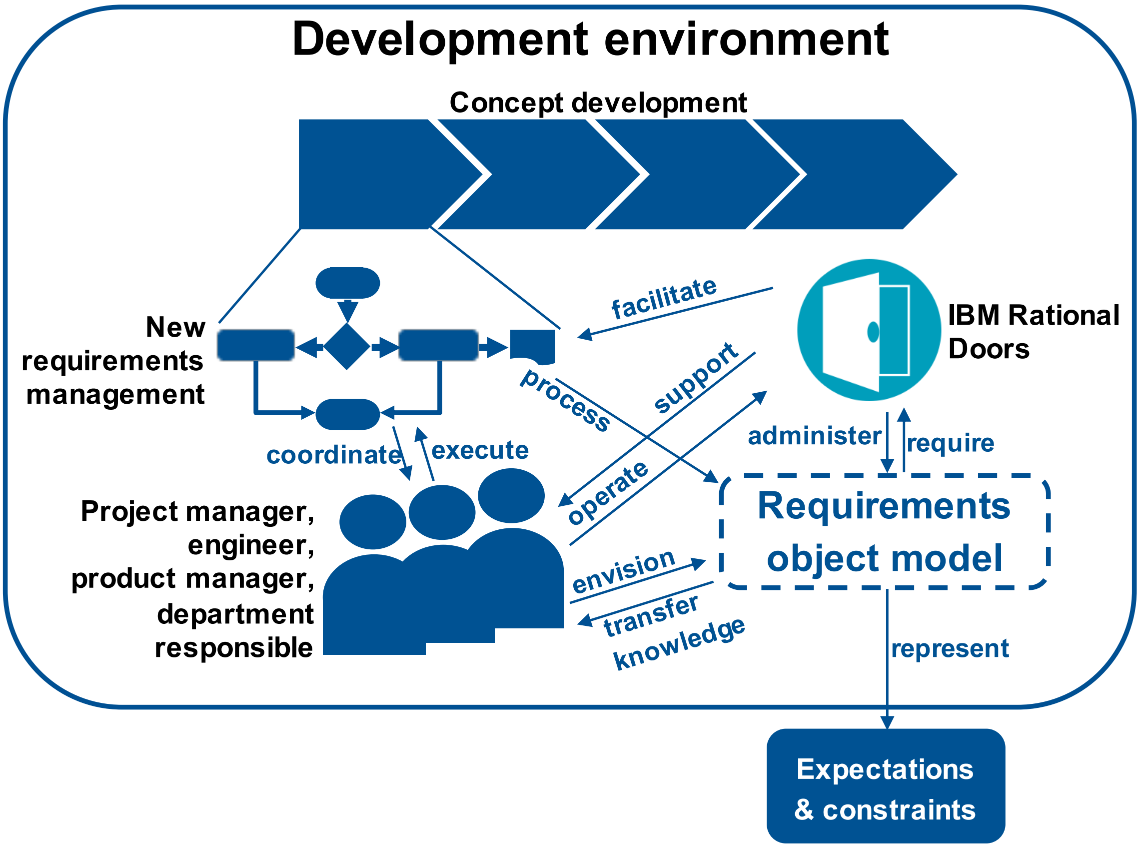

Figure 5-2: Target development environment for the management of requirements during concept development at the automotive OEM

Define transformation approach

Next, the head of development has to choose the parameters of the transformation approach.

As the head of development decided to introduce a new model, his approach can be considered a clean sheet approach to model integration. He now has to decide if he wants to reuse the information from the specification sheet or if a requirements definition should be carried out from sketch. As the former requirements have been widely recognized as adequate, he decides to import them into the new model. Thereby, difficulties in defining and achieving the scope of the model are avoided.

For the scope of the adoption, he goes with an organization-wide adoption, as he does not want the departments to run two systems for more time than necessary and might later want to cover the allocation of requirements to tests with the same tool. During the adoption, the extent of the model is closely monitored to remain in a verifiable range.

Transform and validate

Finally, the transformation is validated in a control loop focusing on the transition from the initial to the target state. The loop monitors the decreasing latency time and assures that only one source of information is in existence. After the target state has been reached, the transformation can be regarded as complete and successful.

Summary

Figure 5-3 sums up the depicted practice-inspired case study on requirements management in concept development at an automotive OEM.

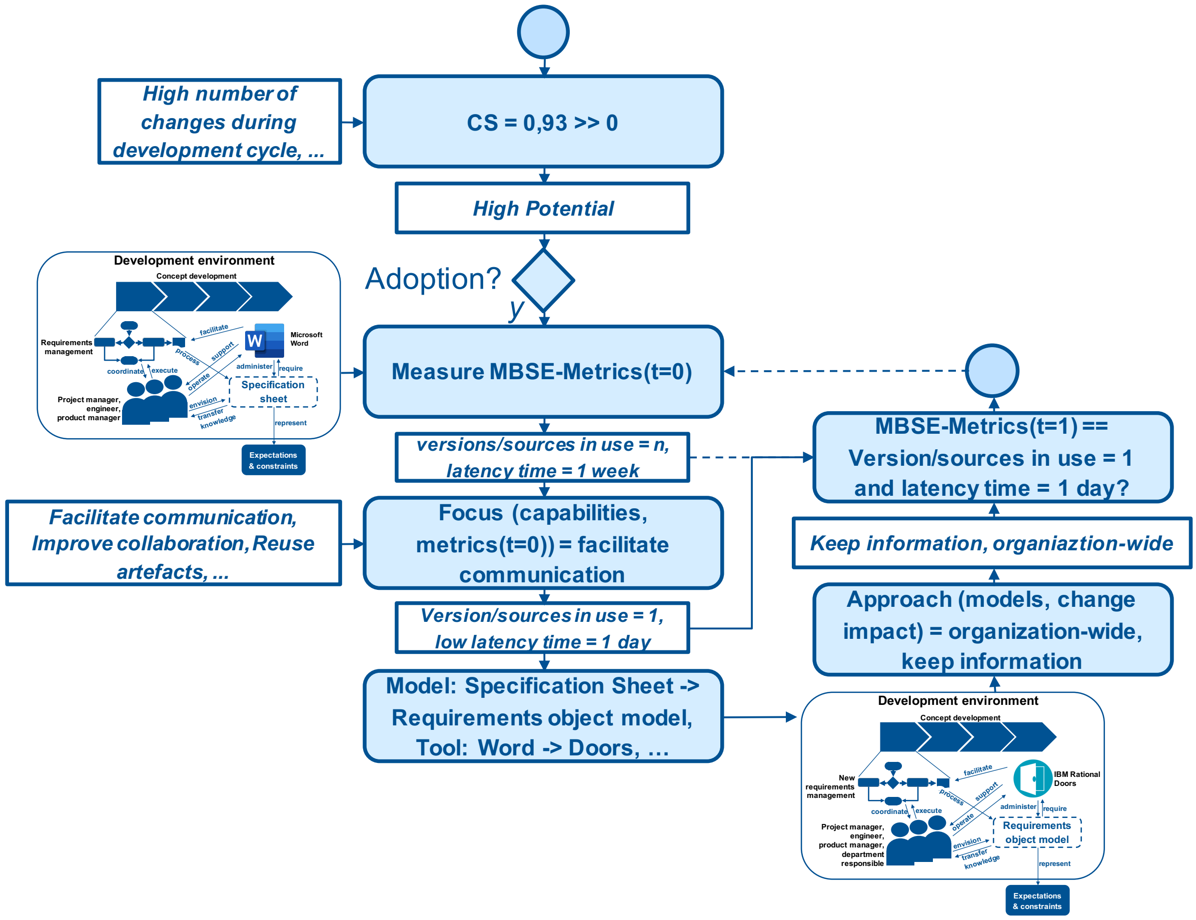

Figure 5-3: Summary of the guideline used on a practice-inspired case study covering requirements management at an automotive OEM

The practice-inspired case study has demonstrated the application of the guideline. It has been proven, that the solution provided by the guideline works regarding the desired functionality.

Therefore, the practice-inspired case study verified the solution and showed its plausibility.

The next subchapter focuses on assessing the usability of the solution regarding the requirements defined in subchapter 1.2.

5.2 Validation

After the functionality has been verified in the previous subchapter, the usability of the guideline will be evaluated in this subchapter. Blessing and Chakrabarti (2009, p.184) propose to use the following questions for the evaluation:

1. *Can the support be used?*
2. *Does the support indeed address those factors it is supposed to address directly (the Key Factors)?*
3. *Are these Key Factors affected as expected?*

To answer these questions, the expert interviews and the requirements defined in subchapter 1.2 are used.

1. ***Can the support be used?***

Although the practice-inspired case study cannot replace a real case study, it was sufficient to verify that the guideline can be used. The presented application of the guideline to the practice-inspired case study has been briefly presented to experts, who did not formulate concerns regarding usability. Therefore, the usability of the guideline can be seen as given, although it should be proven through conducting a real, industrial case study.

2. ***Does the support indeed address those factors it is supposed to address directly (the Key Factors)?***

The key factors the guideline is supposed to address directly were identified in subchapter 1.2. How they are addressed by the presented guideline is recapitulated below.

Assessment of the aptitude for MBSE

The first key factor which the guideline is supposed to address is the assessment of the aptitude of MBSE for an organization. Therefore, key characteristics of an organization's product and development task have been used to determine the complexity prevailing in the product and development task of the organization. A high complexity indicates a high improvement potential achievable through adopting MBSE.

The points raised in the review of the state of the art, specifically addressing which characteristics should be considered for categorization and why as well as the estimation of the potential on an organizational level, have been covered. The factor can thus be seen as fully addressed.

Understanding MBSE capabilities

The second factor is supporting organizations in understanding capabilities offered by MBSE. In order to do so, a literature study identifying excellence improvements through MBSE mentioned in different sources has been carried out. The identified excellence improvements have been clustered and aggregated to form general MBSE capabilities.

The excellence improvements observed in industrial case studies have been combined with the ones listed in scientific and standard works to reflect all capabilities. The emerged list of MBSE capabilities combined with the extensive subchapter about the fundamentals of MBSE fosters the organizations understanding of MBSE capabilities.

Management of the MBSE implementation

To address the third factor, the management of the MBSE implementation, a metrics-based management of the implementation has been proposed. Therefore, metrics covering shortcomings in existing development environments and improvements achieved through adopting MBSE have been elaborated from expert interviews. These metrics form a baseline for the creation of organization-specific metrics to monitor, successfully steer, and justify the MBSE implementation, as described in the guideline.

The elaborated metrics satisfy the aspects highlighted in the review of the literature study. These were, linking the metrics to objectives, describing their measurement and being significant indicators of the MBSE effects. More work is needed to further mature metrics and management approach to fully support the management of the MBSE implementation in practice. Therefore, this factor is partially fulfilled.

Systematic MBSE transformation of the environment

The fourth factor to be addressed by the guideline is the systematic transformation of the complex, existing development environment towards MBSE. To address this factor, a general structure of typical development environments has been worked out in a literature study and has been evaluated in the expert interviews. The structure consists of elements and their relationships to each other and is used in the guideline to systematically address the transformation and evaluate its impacts.

The environment structure unifies different views and aspects of the transformation and the evaluation in expert interviews ensures practicability. Therefore, it provides a decent basis for the MBSE transformation. In combination with the guideline, a systematic transformation of the environment is supported.

Applying a structured MBSE transformation approach

The final addressed factor is the application of a structured MBSE transformation approach. Friedenthal et al. (2015) present an excellent transformation approach, which was identified in the literature review. The presented guideline incorporates this approach, gives a reproducible explanation of its creation and demonstrates its application on a practice-inspired case study. Furthermore, the scope of the adoption and modeling approach are further examined. Therefore, the guideline supports the application of a structured MBSE transformation approach but should be tested under real world circumstances. Table 5-3 summarizes the evaluation of the key factors outlined in this subchapter.

Table 5-3: Evaluation of the guideline addressing the five key factors

	Assessment of the aptitude for MBSE	Understanding MBSE capabilities	Management of the MBSE implementation	Systematic MBSE transformation of the environment	Applying a structured MBSE transformation approach
Guideline for the implementation of MBSE	●	●	◑	●	◕

3. *Are these Key Factors affected as expected?*

After it has been evaluated that the key factors are addressed, it has to be assured that they are appropriately addressed. To evaluate if the key factors are affected as expected, each of them is compared against the quality standards for conclusions defined in subchapter 1.2 reproducibility, reliability, authenticity, transferability, and application.

Assessment of the aptitude for MBSE

The presented assessment of the aptitude for MBSE is achieved through an estimation of the prevailing complexity using key characteristics of the product and development task. As the derivation of the assessment approach is thoroughly documented, reproducibility is given. The reliability and authenticity of the approach both rely on the representability of the survey sample for the population. As the survey sample is heterogenous and experienced, reliability and authenticity of the approach should be covered. The transferability from organization to organization has been a tacit requirement, which was achieved through using general characteristics and incorporating multiple industries. The application of the assessment approach was shown in the practice-inspired case study and can easily be done through the provided formulas. Also, the characteristics are general enough to be easily obtained in any organization. Table 5-4 depicts the evaluation results.

Table 5-4: Evaluation result for the factor assessment of the aptitude for MBSE

Factor	Reproducibility	Reliability	Authenticity	Transferability	Application
Assessment of the aptitude for MBSE	●	◕	◕	●	●

Understanding MBSE capabilities

MBSE capabilities have been derived through clustering and aggregating excellence improvements identified in a study of diverse literature sources. The aggregation and clustering have been carried out in transparent ways, enabling others to reproduce it. The reliability of the capabilities has been ensured through combining contributions from completed, industrial case studies and theoretical works. The authenticity of the capabilities has been positively evaluated in the expert interviews. Improvement potential could be in further confining and relating the capabilities. The capabilities formulated at a high-level are fully transferable between disciplines and industries. Their application in understanding what value MBSE offers, is described in the guideline and practice-inspired case study. It should further be examined in an authentic organizational setting. Table 5-5 shows the evaluation results.

Table 5-5: Evaluation result for the factor understanding MBSE capabilities

Factor	Reproducibility	Reliability	Authenticity	Transferability	Application
Understanding MBSE capabilities	●	●	◕	●	◕

Management of the MBSE implementation

The management of the MBSE implementation is supported through examining metrics currently used to describe improvements achieved through adopting MBSE. These metrics are an essential part of the guideline, which proposes a metrics-based management approach to the MBSE implementation. The reproducibility of the metrics and approach is ensured through providing detailed information on how and why they are measured. The reliability and authenticity of the concrete metrics derived from the expert interviews is high, as they are or have been successfully used in practice. The reliability of the management approach proposed in the guideline has to be further examined in industrial applications, whereas the authenticity has been ensured by the practice-inspired case study. The management approach is transferable, but the concrete metrics transferability is limited. The need for meaningful and organization-specific metrics is highly emphasized. The application of the management approach has to be proven under real world conditions. The derived metrics have been or are currently applied, but more work could be done to facilitate the determination of suitable organization-specific metrics. Therefore, an industrial case study would also be vital. Table 5-6 sums up the evaluation results for this factor.

Table 5-6: Evaluation result for the factor management of the MBSE implementation

Factor	Reproducibility	Reliability	Authenticity	Transferability	Application
Management of the MBSE implementation	●	◕	●	◑	◑

Systematic MBSE transformation of the environment

To systematically transform the complex, existing development environment, the general structure of typical development environments was determined and used in the guideline. To achieve reproducibility, the literature study leading to the environment structure is depicted. The reliability of the derived environment is given, as it is derived from acknowledged literature. The authenticity and applicability have been ensured through evaluating the environment in expert interviews. Regarding authenticity, as the environment is mainly a high-level framework for improving understanding and systematic action, the environment presented environment is not the sole alternative. Therefore, it should be questioned regarding internal contradictions and improved steadily. Transferability between organizations is limitless, but as the environment unifies multiple views and incorporates many aspects, another form of the environment could be more effective for tasks other than the guideline presented in this work. Table 5-7 visualizes the evaluation results.

Table 5-7: Evaluation result for the factor systematic MBSE transformation of the environment

Factor	Reproducibility	Reliability	Authenticity	Transferability	Application
Systematic MBSE transformation of the environment	●	●	◕	◕	●

Applying a structured MBSE transformation approach

The guideline has been developed to support the application of a structured transformation approach. Transferability is addressed through the documentation of the creation of the guideline. The reliability of the guideline has been proven through the practice-inspired case study. The authenticity and application of the guideline have initially been assessed by the practice-inspired case study but should be fully assessed in a real case study. The guideline is highly transferable and could even be used to assess and adopt other methodologies. Table 5-8 displays the evaluation results.

Table 5-8: Evaluation result for the factor applying a structured MBSE transformation approach

Factor	Reproducibility	Reliability	Authenticity	Transferability	Application
Applying a structured MBSE transformation approach	●	●	◑	●	◑

Table 5-9 summarizes the resulting evaluation of key factors.

Table 5-9: Summary of evaluation result for the factors

Factor	Reproducibility	Reliability	Authenticity	Transferability	Application
Assessment of the aptitude for MBSE	●	◕	◕	●	●
Understanding MBSE capabilities	●	●	◕	●	◕
Management of the MBSE implementation	●	◕	●	◑	◑
Systematic MBSE transformation of the environment	●	●	◕	◕	●
Applying a structured MBSE transformation approach	●	●	◑	●	◑

The obtained results are further discussed in the following subchapter.

5.3 Discussion of results

The research presented in this thesis was guided by the research question:

How can Model-based Systems Engineering be meaningfully and successfully implemented, to improve the excellence of existing, complex product development environments?

The strengths and weaknesses of the contributions towards this question outlined in the previous chapter are discussed here. First, the strengths will be elaborated, before the subchapter ends with the weaknesses and a summary.

Strengths

This thesis points out a couple of research gaps and covers **fundamental research** on aspects like development environments and MBSE metrics. This is due to the fact that MBSE is a rather young discipline (Reichwein & Paredis, 2011, p.1) and is still maturing. These contributions are expected to help mature MBSE and foster further research on these aspects.

The insights presented in this thesis, especially from the survey, imply a **high-level of cogency**. This stems from the use of results from significant statistical analysis carried out on a big dataset obtained from a heterogenous and qualified sample. The frequent and continuous performance of support evaluations during the prescriptive study phase adds to this cogency for non-survey related results.

The presented contributions incorporate a **holistic view on the problem** to be solved. They cover and consider the problem from multiple viewpoints to give the reader an understanding of all impacted aspects. This strength is seized in the following weakness, as it is up to the reader to decide if the holistic approach is a strength or weakness.

Weaknesses

The broad scope of this thesis with its five research objectives, tends to conceal the individual contributions. The MBSE methodology is a powerful as well as divers methodology and the focus on its implementation in complex, existing product development environments adds even more scope to that. Describing a holistic approach to the mentioned **problem requires to trade off** the detailed examination of individual aspects against the comprehensive and transferable depiction of the whole. Therefore, it is up to the reader to decide whether this thesis succeeded or failed in accomplishing this trade-off.

Although a lot of support evaluation as well as validation of partial results has been continuously carried out and the practice-inspired case study verified the guideline, there is **no** validation of the **guideline** in an **industrial case study**. Conceptualization of the guideline and real case study would go beyond the scope of a master's thesis. Therefore, an authentic industrial case study and thereby success evaluation should be addressed in a research project.

Table 5-10 summarizes the discussed strengths and weaknesses of the presented work, before the next subchapter reflects on the applied methodology.

Table 5-10: Summary of the discussed strengths and weaknesses

Strengths	Weaknesses
○ Fundamental research ○ High-level of cogency ○ Holistic view on the problem	○ General description of detailed aspects ○ No industrial case study on the guideline

5.4 Reflection of the methodology

The methodology applied in this thesis is reflected in this subchapter.

The general research methodology used in this thesis is the **Design Research Methodology** (DRM) by Blessing and Chakrabarti (2009), which has been proofed to be useful in design research. As most of the research in this thesis is design related (see subchapter 1.4), it was an **accurate choice**.

Going into more detail, literature reviews, a survey, and expert interviews have been conducted in the phases of the DRM framework.

Literature studies have been used to formulate the research goal, describe the current state of research, and derive fundamental concepts. The extensive studies spanned multiple search portals and covered a **broad scope** of publication styles. The procedure and **results** have been outlined and **structured accordingly**. Interesting secondary works found in the retrieved primary works, complicate the reproducibility of the procedure. The literature studies provided a broad overview and the fundamentals of the thesis.

For the **survey**, the MBSE online course of the MIT has been used. The **sample** of survey candidates is **credible and divers**, as section 3.3.1 shows. The creation of the survey questionnaire could have been supported through a methodology. To analyze the survey data, **reliable** statistical **analyses** have been used and explained in subchapter 0. The significant results and interpretations are representative for the survey sample. They delivered a broad understanding of the current practical state.

The **expert interviews** were conducted to further enrich the understanding of the current practical state. Experts from multiple organizations in the **automotive and commercial vehicle industry** have been interviewed. Other industries should have been included, but there has not been a comparable number of available experts by other industries. The semi-formal interviews were orientated on a questionnaire, ensuring the **right thematic focus** and comparability of answers. The obtained **results** were **outlined** and discussed **accordingly**.

Concluding, the **combination** of literature studies, survey, and expert interviews yields a **good mixture of overview and in-depth insights** as well as of **theory and practice**. The work presented in this thesis and verified and validated in this chapter is concluded and extrapolated in the following chapter.

6 Conclusion and outlook

This chapter concludes the presented work and gives an outlook on future research connected to the matter at hand. The first subchapter covers the conclusion and the second the outlook.

6.1 Conclusion

The thesis presented contributions to the meaningful and successful implementation of MBSE in existing, complex product development environments to improve their excellence.

It has been proven that the potential achievable through an MBSE adoption is proportional to the complexity prevailing in an organization. A cogent approach to the estimation of the prevailing complexity has been introduced.

A literature study identified excellence improvements related to the adoption of MBSE. These improvements have been clustered and aggregated to form general MBSE capabilities. These capabilities allow a deeper understanding of what MBSE can provide.

Regarding the implementation of MBSE, a metric-based management approach has been proposed. Additional to the management approach, exemplary metrics measuring the success of the MBSE transformation have been identified and their measurement has been described. Enabling a more sophisticated conversation about appropriate, organization-specific metrics measuring MBSE success.

Fundamental research has been carried out to depicting a general development environment structure, influenced through MBSE. The presented environment supports organizations in building a suitable MBSE methodology and evaluating its impacts.

Finally, a guideline incorporating all of the contributions above was presented to equip MBSE adopters with a structured MBSE transformation approach, emphasizing a meaningful and successful transformation.

Discussing the carried-out research methodology revealed the high cogency of the presented, partly fundamental insights, the need for an extensive industrial case study and identified a trade-off between a holistic view and detailed description of parts.

6.2 Outlook

Future research connected to the presented matter should be carried out. From a broad field of research opportunities, four non-exclusive, major research agendas linked to the contributions of this thesis are briefly depicted here.

First, as discussed, an **industrial case study** should be realized in a **research project** to further evaluate the guideline in practice. This would help optimize the guideline as well as contributions made in this thesis. Also, an industrial case study would evaluate its success in the form of a *"success evaluation"* as coined by Blessing and Chakrabarti (2009, p.185). The pre-requisites to start a success evaluation, being support and application evaluation, have been met through this thesis. A promising setting for the success evaluation would be an organization that is currently evaluating the use of MBSE in its prevailing development environment and is open to change.

Second, the fast amount of **insights gained from the survey dataset**, which was **not covered** in this thesis, **should be published**. As the survey questionnaire in appendix A2. shows, four questions, like “Which MBSE software tools are you presently using to support which MBSE task?“ are not covered in the survey analysis in section 3.3.3. This question in particular generated unique data about the association of certain MBSE tools to the systems engineering tasks, which should be used to optimize tool application as well as the tools themselves. Prework has been done on the interpretation of significant results, which can be used as a basis for further discussion and publications by and with other authors.

Third, the insights gained from the survey data **indicate shortfalls of the current MBSE methodologies**, like difficult to achieve model qualities or difficulties in convincing others of the value of MBSE. This thesis offered initial interpretations and solution approaches to the shortfalls, but each of them **should be examined thoroughly** in other works. The depicted shortfalls underline a strong motivational case for such research endeavors.

Finally, the **fundamental research** carried out in this thesis should be **used as a starting point** for further research maturing the aspects: MBSE capabilities, generic development environment, and MBSE success metrics. Especially, the research on MBSE success metrics and development environment structures seems to be promising in enabling organizations to grasp the benefits provided through the MBSE methodology, as survey data has shown that the organizations would prefer more guidance in the implementation of MBSE (see subchapter 1.1).

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List of abbreviations

ANOVA	Analysis of Variance
CAD	Computer-aided Design
DoD	Department of Defense
DRM	Design Research Methodology
DS	Descriptive Study
DSM	Design Structure Matrix
FMEA	Failure Mode and Effect Analysis
INCOSE	International Council on Systems Engineering
IT	Information Technology
KMO	Kaiser-Meyer-Olkin
KPIs	Key Performance Indicators
KSAs	Knowledge, Skills and Abilities
MBD	Model-based Design
MBE	Model-based Engineering
MBSD	Model-based Systems Development
MBSE	Model-based Systems Engineering
MDD	Model-driven Development
MDE	Model-driven Engineering
MIT	Massachusetts Institute of Technology
OEM	Original Equipment Manufacturer
OMG	Object Management Group
OPAC	Online Public Access Catalogue
PCA	Principal Component Analysis
PhD	Doctor of Philosophy
PS	Prescriptive Study
ROI	Return-on-investment
SE	Systems Engineering
SEDE	Systems Engineering Development Environment
SST	Single-source-of-truth
SysML	Systems Modeling Language
TUM	Technical University of Munich

UML	Unified Modeling Language

Appendix

A1 Survey questionnaire

MBSE MOOC Survey

Start of Block: Course start

Do you manage more than 10 team members (directly or indirectly)?

- ○ Yes
- ○ No

What is the magnitude of your organization's typical unit cost?

- ○ $ 1 - 100
- ○ $ 100 - 1,000
- ○ $ 1,000 - 10,000
- ○ $ 10,000 - 100,000
- ○ $ 100,000-1,000,000
- ○ $ 1,000,000 - 10,000,000
- ○ > $ 10,000,000
- ○ Unknown to me

What is the part count of your organization's typical product?

- ○ 0
- ○ 1 - 10
- ○ 10 - 100
- ○ 100 - 1,000
- ○ 1,000 - 10,000
- ○ 10,000 - 100,000
- ○ 100,000 - 1,000,000
- ○ > 1,000,000
- ○ Unknown to me

How many source lines of software code are there in your organization's typical product?

- ◯ 0
- ◯ 1 - 10
- ◯ 10 - 100
- ◯ 100 - 1,000
- ◯ 1,000 - 10,000
- ◯ 10,000 - 100,000
- ◯ 100,000 - 1,000,000
- ◯ > 1,000,000
- ◯ Unknown to me

How many different disciplines (functional specialized groups using specific knowledge & tools distinguishing them from other groups) are involved in a typical product development project in your organization?

- ◯ 1
- ◯ 1 - 5
- ◯ 5 - 10
- ◯ 10 - 20
- ◯ 20 - 30
- ◯ 30 - 50
- ◯ > 50
- ◯ Unknown to me

How long is your organization's typical development cycle time in months?

- ◯ < 1
- ◯ 1 - 6
- ◯ 6 - 18
- ◯ 18 - 36
- ◯ 36 - 60
- ◯ 60 - 120
- ◯ > 120
- ◯ Unknown to me

What is the approximate number of full and part time employees involved in a typical product development project of your organization?

- ◯ 1 - 10
- ◯ 10 - 50
- ◯ 50 - 100
- ◯ 100 - 500
- ◯ 500 - 1,000
- ◯ > 1,000
- ◯ Unknown to me

How many major changes (budget cut, major change in requirements, new technology added, ...) occur in a typical product development project of your organization?

- ○ 0
- ○ 1
- ○ 1 - 5
- ○ 5 - 10
- ○ 10 - 20
- ○ 20 - 100
- ○ > 100
- ○ Unknown to me

How many direct contractor/supplier organizations (in a contractual relationship with your organization) are there for your organization's typical product development project?

- ○ 0
- ○ 1
- ○ 1 - 5
- ○ 5 - 20
- ○ 20 - 50
- ○ 50 - 100
- ○ 100 - 1,000
- ○ > 1,000
- ○ Unknown to me

Which of these might make it difficult to convince others of the value of MBSE for your organization? (Select all that apply.)

▢ MBSE concepts are too high-level to be implemented in practice

▢ Lack of guidelines on how to implement MBSE

▢ Too hard to find best MBSE practices

▢ Too many different claims about what MBSE is or isn't

▢ There is insufficient clear value from MBSE

▢ Individual pilot studies can not fully demonstrate the potential value of MBSE

End of Block: Course start

Start of Block: Week 1

For your organization, which approach is more likely to be adopted?

○ Ground up / clean sheet

○ Tying existing models together

What is the primary approach your organization uses in its adoption of MBSE? (Select one.)

○ Adoption by individuals in their workflows, but not at the project or organizational level

○ On a project by project basis, but not organization-wide

○ As part of a larger transformation program

○ We are not yet adopting MBSE

Rank your organization's priorities in it's MBSE transformation (1 being the first/highest priority; 2 the second highest priority, and so on, with a blank entry meaning no priority in the transformation).

1. ______ Process & Workflows - Logical sequence of tasks performed to achieve a particular objective
2. ______ Methods & Models - Techniques for performing a task
3. ______ Software Tools - Instruments enhancing the efficiency of the task
4. ______ Organizational culture - Social and psychological environment of the organization (informal relationships)
5. ______ Organizational structure - Hierarchy within an organization (formal relationships)

Which qualities of great models do you think will be the most difficult to achieve in MBSE?

(Select all that apply.)

- ☐ Linked to Decision Support
- ☐ Model Credibility
- ☐ Clear Scope
- ☐ Verification and Validation with Models
- ☐ Understandable and Well-Organized
- ☐ Analyzable and Traceable
- ☐ Data Extrapolation
- ☐ Complete Relative to Scope and Intended Purpose
- ☐ Internally Consistent
- ☐ Verifiable
- ☐ Validation
- ☐ Model Fidelity
- ☐ Elegant
- ☐ Well Formed for Optimization
- ☐ Avoid Optimizing on a Black Box
- ☐ Availability of Interfaces

☐ Reusable

End of Block: Week 1

Start of Block: Week 2

In your organization, what is the primary mode of capturing system data? (Select one.)

○ Model based

○ Mix of both however predominantly model

○ Mix of both however predominantly document

○ Document based

End of Block: Week 2

Start of Block: Week 3

Rank your organization's emphasis on MBSE (1 being the area of focus with the greatest emphasis; 2 the second greatest emphasis, and so on, with a blank entry meaning no emphasis on that MBSE area).

6. _______ Facilitate communication by using a single and up-to-date source of information
7. _______ Improve collaborative, interdisciplinary engineering by establishing a shared system understanding
8. _______ Reuse architecture and engineering work results by documenting previous solutions
9. _______ Reduce development cost and cycle time by improving problem understanding
10. _______ Improve risk assessment, safety considerations and quality assurance through transparency and traceability
11. _______ Improve later lifecycle activities through easily accessible documentation

Does your organization use an MBSE approach?

- ○ Yes
- ○ No
- ○ Not sure

What feature or features do you believe have made the aerospace industry a leader in MBSE? (Select all that apply.)

- ☐ Project/Product complexity
- ☐ Regulatory environment
- ☐ High development cost
- ☐ Emphasis on the whole product lifecycle

Have you ever been asked to formally evaluate / critique an MBSE approach?

- ○ Yes
- ○ No
- ○ Not sure

End of Block: Week 3

Start of Block: Week 4

Do you think MBSE should be implemented in your organization?

- ◯ Yes
- ◯ No
- ◯ Not sure
- ◯ Already implementing MBSE

End of Block: Week 4

Start of Block: Questions not covered in this thesis

Which MBSE software tools are you presently using to support which MBSE task? (Select all that apply.)

	Not using this tool	Managing requirements	Building system architecture diagrams	Doing detailed design of parts or code	Conduct system level quantitative analysis	Verifying and validating systems
ChangeVision Astah SysML	☐	☐	☐	☐	☐	☐
ConceptDraw SysML Solution	☐	☐	☐	☐	☐	☐
Dusan Rodina Software Ideas Modeler	☐	☐	☐	☐	☐	☐
Esterel Technologies SCADE System	☐	☐	☐	☐	☐	☐
IBM Rational Rhapsody/Doors	☐	☐	☐	☐	☐	☐
Lattix Architect	☐	☐	☐	☐	☐	☐
Modeliosoft Modelio	☐	☐	☐	☐	☐	☐
No Magic Cameo Systems Modeler/MagicDraw	☐	☐	☐	☐	☐	☐
Object Management Group (OMG) Visual Paradigm for UML	☐	☐	☐	☐	☐	☐
OPCAT	☐	☐	☐	☐	☐	☐
Papyrus	☐	☐	☐	☐	☐	☐

PolarSys Capella	☐	☐	☐	☐	☐	☐
PolarSys Topcased	☐	☐	☐	☐	☐	☐
PTC Integrity Modeler	☐	☐	☐	☐	☐	☐
Sparx Systems Enterprise Architect	☐	☐	☐	☐	☐	☐
SPEC Innovations Innoslate	☐	☐	☐	☐	☐	☐
SysML Designer	☐	☐	☐	☐	☐	☐
Vitech CORE	☐	☐	☐	☐	☐	☐
Vitech GENESYS	☐	☐	☐	☐	☐	☐
Mathworks System Composer	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐

Do you think MBSE is sufficiently mature to warrant actions today? (Select one.)

- ◯ No
- ◯ Not sure
- ◯ Yes, MBSE is mature enough to create models using a standard language
- ◯ Yes, MBSE is mature enough to execute models and facilitate model verification
- ◯ Yes, MBSE is mature enough to create integrated system models that include other engineering and functional discipline models
- ◯ Yes, MBSE is mature enough to make models parametric in nature and facilitate reuse and patterning

MBSE will be a big hit in:

- ◯ It already is!
- ◯ 2021
- ◯ 2030
- ◯ I don't think it will be a big hit

What’s the most sophisticated query type you’ve written? - Selected Choice

- ◯ I’ve asked my co-workers to run queries, but I haven’t written a query myself
- ◯ I've manually sorted through a series of documents
- ◯ I've put data in spreadsheets
- ◯ I've used simple databases like MS Access
- ◯ I've used databases like SQL
- ◯ Other, please specify:

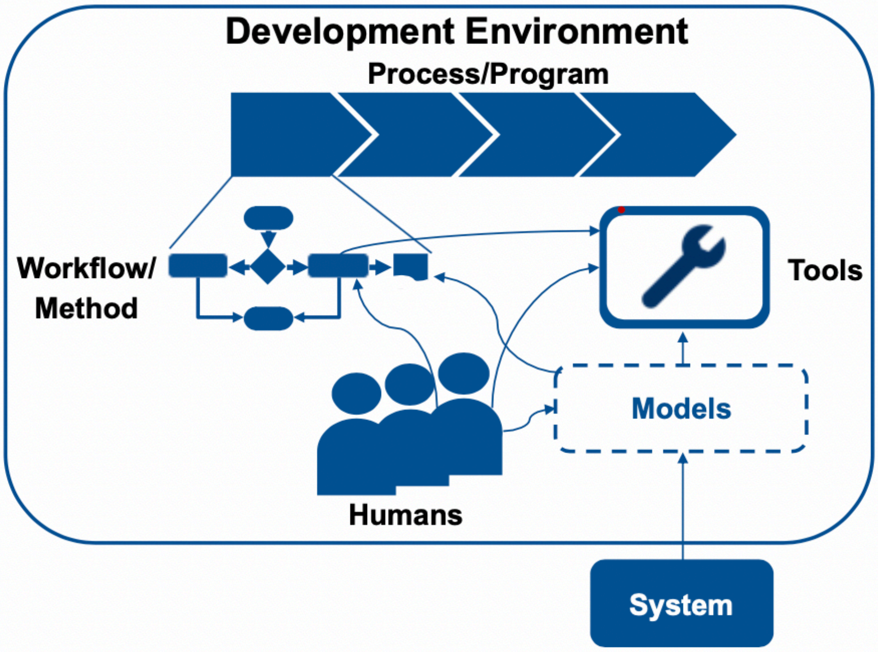
End of Block: Questions not covered in this thesis

A2 Interview guideline

Expert Interview Guideline – Model-based Environments for Systems Development

1. Development Environment

Is your organization's development environment adequately described by the environment depicted in the following graphic (derived from literature)? If not, are there elements/relationships missing or should be further defined?



Which elements and relationships of this environment can be subject to changes and are most likely to change in the digital transformation of your company?

2. Digital Transformation: Objectives & Metrics

What are your company's main objectives in the digital transformation of its product development efforts? (e.g. Facilitate communication; Improve collaborative, interdisciplinary engineering; Reuse architecture and engineering work results; Improve risk assessment, safety considerations and quality assurance; Facilitate later lifecycle activities)

Which metrics does your company use to measure the success of a (digital) transformation approach in product development? (e.g. ROI, development cycle time, metrics coupled with objectives)

How does your company assess the applicability of technologies (tools) and techniques (methods/models) to improve the current development process?

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3. Current Use of Models and Systems Engineering

Are your organization's development efforts rather document- or model-based? An example for document-based requirements management would be the use of a specification sheet, whereas a model-based approach would be the use of a requirements management tool)

What kind of models and tools are currently used in your company's development efforts? (e.g. IBM Rational Doors for requirements management, Dassault Systems CATIA for CAD) Are they sufficiently integrated in the overall model- and toolset?

Are your company's development efforts described in a process framework and are models part of this framework (e.g. as deliverables, review objects)?

Does your organization use Systems Engineering in any form? If yes, please specify the form; If not, why is it not used?