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COST-BENEFIT ANALYSIS IN MODEL-BASED SYSTEMS ENGINEERING: STATE OF THE ART AND FUTURE POTENTIALS

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Abstract

The increasing complexity and shorter time-to-market cycles demands enhancement methods for conceptual design phases. An instrument to promote product development activities by enlarging document-based methods on system level via increasing modeling effort is Model-Based Systems Engineering (MBSE). The intention of shifting this effort into early phases by frontloading-concepts on the one hand should reduce costs in the series development on the other. The resulting cost-benefit coherences of these correlations on system level as a symbiosis of mechanical-, electrical- and software engineering is currently a small highlighted research topic. Therefore, the paper analyzes the recent state of the art by evaluating industrial cost-benefit-theories in MBSE. The summary of existing industrial studies and indicators transferred to thereof resulting cost-benefit models consolidates a lack of research regarding the product system level. An initial approach to create new indicators, based on recorded expert interviews, for the development of an industrial MBSE benefit-model regarding costs is focussed after this summary. For this model, a MBSE pilot project in industry is discussed

Keywords: Systems engineering (SE), Mechatronics, Early design phases, Design costing

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1 INTRODUCTION

The increasing complexity of new products and organisations towards a shorter development cycle needs new design methodologies and processes especially in the early stages of product development (Eigner et al., 2014). Furthermore, the interconnection of single design domains is increasing drastically. The number of electronic and software parts has grown the last few years up to 40% for example in the automotive industry (ITQ, 2014). Costs are also affected by this rising complexity and are focused in respective literature, e.g. in Ehrlenspiel et al. (2013). These design costs are one of the main arguments for time reduction on management level in huge organisations. The increasing number of product recalls (e.g. Bertsche et al., 2009) is an expensive consequence of this lack in handling product complexity. This complexity concerns especially the automotive industry as well as mechatronic systems in general. Figure 1 illustrates the coherence of effort and costs over time regarding classic development effort as well as model-based development effort.

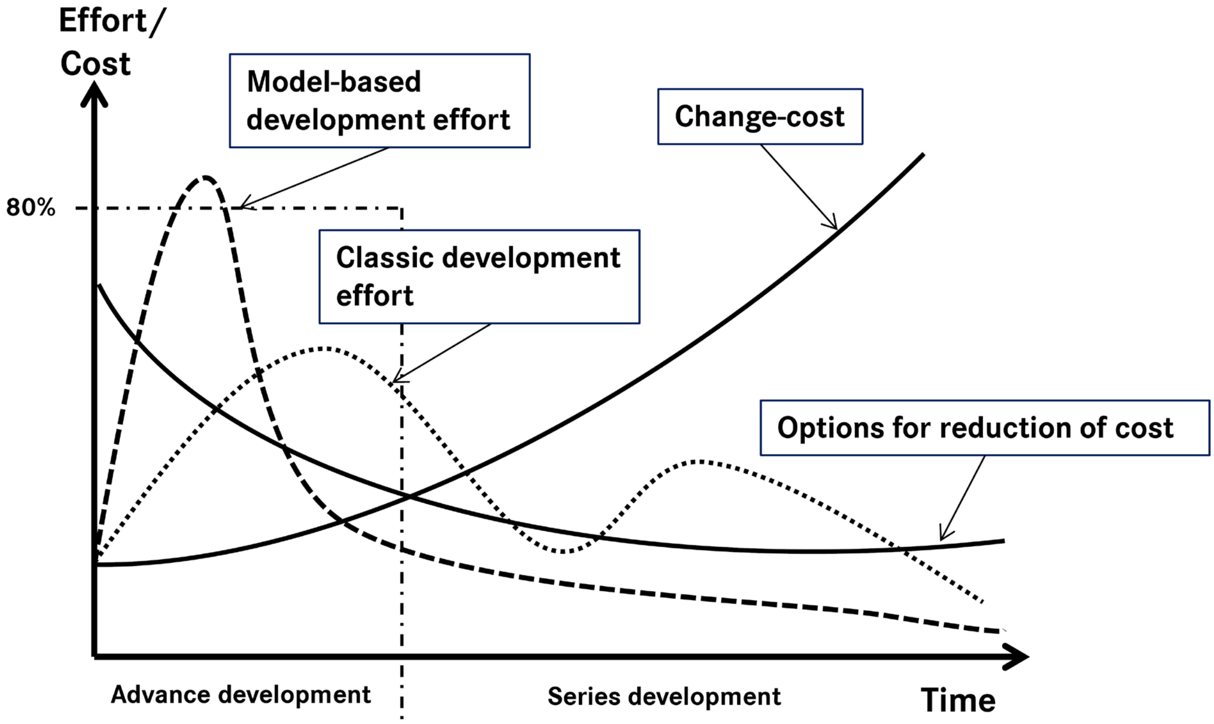

Figure 1. Effort/cost dependency over time based on Eigner and Stelzer (2009), Albers and Nowicki (2003)

Figure 1 is only a qualitative representation out of many, e.g. in the VDI guideline 2235 (VDI, 1987), visualizing the importance of this early conceptual phase. In contrast to these figures, existing research activities to underline such numbers on Model-Based Engineering are actually less propagated (Mohagheghi and Dehlen, 2008). In general, a benefit analysis evaluated in industrial companies regarding costs isn't sufficiently elaborated yet (Sikora et al., 2011). Valid indicators as well as operation numbers build the basis for these kinds of investigations within a resulting performance model. An instrument to promote the early product development activities by enhancing document-based methods on system level is Model-Based Systems Engineering (MBSE) (Friedenthal et al., 2009). The shifting of the development effort into the conceptual phase to early increase the deepness of informations of new products by MBSE is also listed under the name "frontloading". The authors goal of this paper is to analyze the recent research activity and analysis approaches concerning cost-benefit of Model-Based Engineering in domain specific engineering disciplines in section 3 after a short introduction of MBSE and existing methodologies in general in section 2. The missing model on the interdisciplinary system level is a result of this study. In section 4, the authors propose a first approach for working out a model for cost-benefit-analysis in MBSE based on existing processes and organisation infrastructure. Therefore, they analyze expert interviews to identify specific potentials for new indicators focussed in MBSE. Section 5 summarizes the work.

2 MODEL-BASED SYSTEMS ENGINEERING

MBSE is a multi-disciplinary engineering paradigm propagating the use of models instead of documents to support analysis, specification, design and verification of the system being developed (Friedenthal et al., 2012). Systems Engineering (SE) as such, impacts technical as well as management processes to generate a balanced system solution in regard to various stakeholder needs and to reduce risks that can hinder the success of a project (Haskins, 2011). Model-based approaches are standard practice in electrical, mechanical and software design since many years. Systems Engineering is transitioning from a document-based approach to a model-based approach like the above-named engineering disciplines (Friedenthal et al., 2012). MBSE offers significant potential benefit for the specification and design of a system. The resulting system model helps to understand and to overview the complexity of the developed system and simplifies the communication in a multi-disciplinary development team from a discipline-neutral view of the system specification.

According to Delligatti (2013), for an effective design as well as for an effective communication between the different stakeholders of a project three things are important to create a promising system model: a modelling language, a modelling tool and a modelling method. Several modelling methods are documented in literature (Estefan, 2008) and can be characterized as methods that implement the whole Systems Engineering process or just parts.

The ISO/IEC 15288 (2008) as international standard defines a framework that describes the lifecycle of a system created by humans. This system engineering standard defines processes as well as a set of associated terminology which cover the whole lifecycle from the conceptual design and development of a system along the production and usage up to the retirement. The Object-Oriented Systems Engineering Method (OOSEM) is a model-based approach written down in the Systems Engineering handbook of the International Council on Systems Engineering (INCOSE) (Haskins, 2011). OOSEM as top down approach supports the specification, analysis, design and verification process of a system by using the modelling language SysML (Friedenthal et al., 2012). It combines object-oriented concepts with traditional system engineering methods to develop more flexible and extensible systems that can accommodate evolving technology and changing requirements. Another methodical guideline for the use of the Model-Based Systems Engineering paradigm has been developed and conceptually realized through extending the V-model from VDI 2206 (2004) in several steps (see Figure 2).

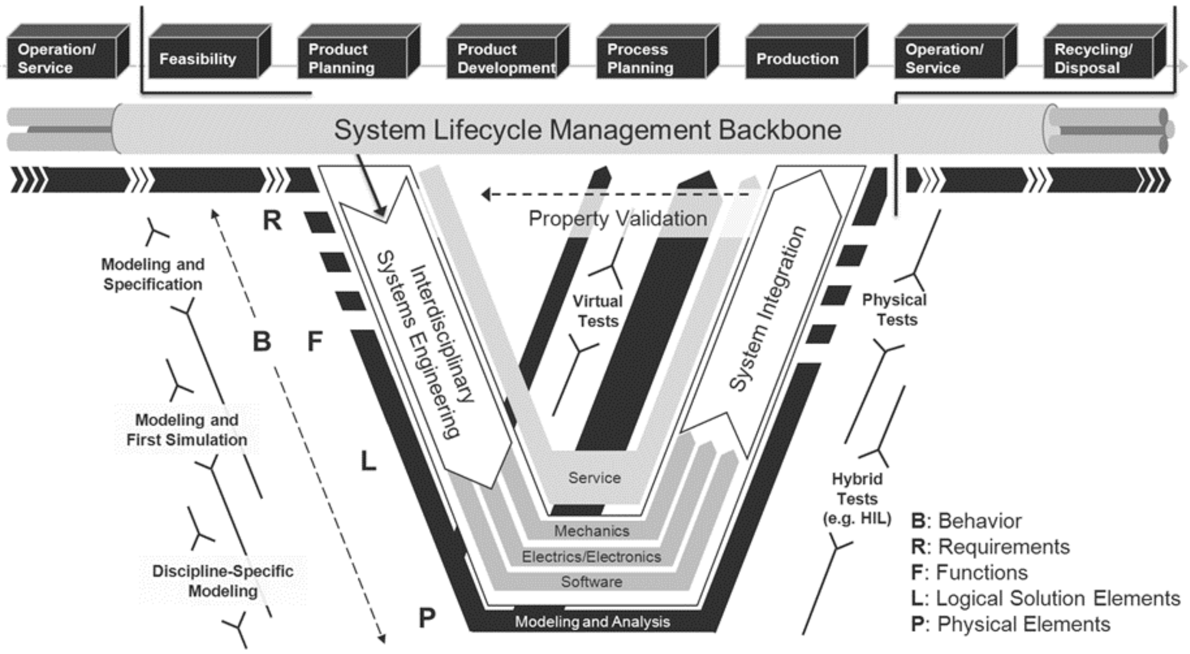

Figure 2. MBSE-model for Multi-Disciplinary Product Development (Eigner et al., 2014)

This MBSE-model for multi-disciplinary product development by Eigner et al. (2012, 2014) in figure 2 enables a model-based and structured system description in the early phases of development. The systemization on the left wing of the V-model divides the system modelling process in the three levels of specification, first simulation and discipline-specific modelling. Parallel to these overlapping levels, the information artefacts or model elements of a system are differentiated in requirements (R), functions (F), logical solution elements (L) and physical parts (P), as well as elements and artefacts which describe the system behaviour (B). The System model is created in an authoring tool by using the Systems Modelling Language (SysML) to describe complex and interdisciplinary products in a formal way. The use of a formal language like SysML guarantees the possibility to administrate, version and reuse the artefacts of a system model. A specific data scheme describes and defines the system elements as well as the semantic links between them to ensure traceability in a 'horizontal' and 'vertical' way. Furthermore, the data schema allows to integrate and to manage this information in a new System Lifecycle Management (SysLM) backbone, defined as the extension of Product Lifecycle Management (PLM) into conceptual phases (Eigner et al., 2014; Gilz, 2014).

Although the benefit of this increasing effort in the conceptual phase by these methods is presumable, valid analyse about this benefit are rarely available. Even the ISO15288 affects cost-benefit topics without going into details by evaluation studies especially in MBSE. Section 3 discusses recent benefit effort by industrial analysis and existing cost benefit theories in general. The missing approach for the system level in product development is the result of this discussion.

3 STATE OF THE ART IN THE EVALUATION OF MODEL-BASED ENGINEERING (MBE) IN INDUSTRY

3.1 Recent Analyse

There are not a variety of studies about the effort in MBE as a method for the conceptual phase. The difference between MBE and MBSE is hardly characterized in literature. The absent addressing of an enhanced interdisciplinary system product level in MBE is nevertheless one of the main differences between the definitions of these two terms. As mentioned before, especially the factor cost over cross-domains isn't characterized enough (Sikora, 2011). The few results from recent studies on particular MBSE in the context of Systems Engineering are carried by insufficient research activity in this topic. A small number of results are provided by a few statements from the International Council on Systems Engineering (INCOSE) or the Object Management Group (OMG), which can be located in literature. Kirstan (2011) exclusively mentioned the synonym MBSE in another context regarding Model-Based Software Engineering at his dissertation. Nevertheless, the following discussed research studies from the past have already evaluated several listed points about the general practice of Model-Based Engineering:

- Utilize of modelling languages and tooling (e.g. Unified Modelling Language, SysML, Modelica)
- Commitment in an isolated design phase (e.g. Requirements Engineering, Architectural Design)
- Usage in a specific development discipline (e.g. Mechanic Engineering, Electrical Engineering, Software Engineering)

In chronological order, the authors analyze this recent main results. The need of new, not only textual based methods in the specification of requirements was already analyzed by Lubars et al. (1992). Davies et al. (2006) are giving a huge summary about the modelling techniques and the existing tooling support for Model-Based Engineering. Mohagheghi and Dehlen (2008) discuss 25 papers regarding the distribution in Model-Driven-Engineering (MDE) in industrial projects. The increasing use of these techniques is thereby one of the main results. Fieber et al. (2009) discuss the new influences by introducing model driven engineering in a large company, analyzed from a recent study.

Important to note with regards to the latest industrial informations about MBE are the results of the paper by Kirstan and Zimmermann (2011) as well as the latest information about the state of the art by using new MBSE languages (Cloutier and Bone, 2012) as the basis for further research activities, particularly discussing the absent cost-benefit-analysis on system level.

Table 1 summarizes the literature research separated by the previously structured categories and furthermore points out the focus on modelling language, design phase or design discipline.

Table 1. Analyzed industrial work in Model-Based Engineering in general

(R: Requirement, F: Function, L: Logical element, P: Physical element)

Category/Author	Design practice	Design phase	Design discipline
Lubars et al. (1992)	Modelling tool	R	Software Engineering
Davies et al. (2006)	Modelling language and tool	F	Software Engineering
Mohagheghi and Dehlen (2008)	Modelling tool	R,F	Software Engineering
Fieber et al. (2009)	Modelling language and tool	F	Software Engineering
Sikora et al. (2011)	Modelling language	R	Software Engineering
Kirstan and Zimmermann (2011)		R,F	Software Engineering
Cloutier and Bone (2012)	Modelling langugage	R,F,L,P	Interdisciplinary design discipline

Section 3.2 analyses opportunities for the measurement of parameters for such studies considering indicators and operating numbers for the construction of cost models. A respective literature research provides the basis for this overview from the authors.

3.2 Recent cost-benefit model theories

3.2.1 Indicators and basics for cost-benefit models

Indicators to measure the benefit in the usability of Systems Engineering in general have been already focussed in several research studies. The authors separate these indicators in two main categories:

- Process indicators (e.g. Engineering change request, Engineering change orders)
- Discipline indicators (e.g. Requirement Trend, Requirements Verification Trends)

A generic term in the description of these process indicators is often corresponding to the key performance indicators (KPI). Olson (2008) describes five basic measures for any kind of product: size, cost, effort, schedule, defects. These five indicators built the foundation for further process measurement activities. VDMA (2013) evaluates several process indicators to support the continued improvement process (CIP) in organisations under the project name PIPE. OMG (2014) provides a wiki with lots of data for MBE and partially MBSE metrics in industrial design effort. The work of Hounour et al. (2005) about the Systems Engineering return of investment (SE-ROI) and Carson (2011) represent only two resources at this point as an example for consisting effort in model-based process analysis. Additionally there are existing web-databases for performance indicators in general, divided by industry, processes or organisations (e.g. KPILibrary, 2014/ 08.12.2014).

Discipline Indicators do not focus on collecting data for an explicit evaluation by engineering numbers. The centrum of this metric is the design discipline itself, particular Model-Based Systems Engineering and Model-Driven Engineering, enlarging development processes. The Systems Engineering leading Indicators Guide from INCOSE (Roedler et al., 2010) addresses several indicators with an explicit focus on Systems Engineering. Therein, different proposals are given for proven measurement of product quality regarding the use of Systems Engineering in the conceptual phase. At the end of this proposal, a relation between cost-benefit and these leading indicators is explained elementarily.

Analysing these different documents regarding cost-benefit-aspects of MBSE, the enhancement of recent indicators and metrics is necessary. Another problem of the listed indicators is frequently addressed in the dependency between multiple indicators, which currently only is considered in the tradeoff analysis from INCOSE (Roedler et al., 2010). Nevertheless, the authors collect first basic examples for cost-benefit indicators, based on the referenced literature. Table 2 presents these examples for already existing, potential indicators in MBSE with short explanations.

Table 2. Indicators for Model-based Systems Engineering

Indicator:	Description:
System Affordability Trends	Indicator e.g. as a percentual quotient between baseline effort and estimated effort to the baseline effort resulting in the change in affordability (Roedler et al., 2010).
Engineering Change Order	Indicator for the number of Engineering Change orders with regards to the project, product, development phase and the change reason (VDMA, 2013).
Schedule and cost pressure	Indicator to evaluate the project benefit by generating pressure with regards to cost and the schedule. This pressure is commited to simple mathematical analysis (Roedler et al., 2010).
Engineering Change Request	Indicator for the number of Engineering Change Request with regards to the project, product, development phase and the change reason (VDMA, 2013).
Requirement Trends	Indicator to collect informations about the growth, change, completeness and correctness of system requirements (Roedler et al., 2010).
Architecture Trends	Indicator to evaluate the maturity of a company with regards to implementation and deployment of an architecture process based on standards and guidelines (Roedler et al., 2010).
Interface Trends	Indicator to evaluate the stability of interfaces with regards to growth, change and correctness of the definition of the system interfaces (Roedler et al., 2010).

These exemplarily listed indicators are representing the basis for the construction of a measurement system for cost-benefit investigations regarding design phases or design methods. The next subsection discusses gained research results in the relation between cost and benefit with regards to scientific models for product development in general, MBE and particularly MBSE.

3.2.2 Cost-Benefit Models

The further development of those indicators is integrated into a specific model to measure the benefits in comparison to the costs by analysing the model-based related parameters. Ehrlenspiel (2013) and Pahl/Beitz (2013) as standard literature discuss such cost-benefit-analyse regarding the entire product lifecycle management cycle. The focus of these authors is the avoidance of costs by designing a lean product specialized in mechanical engineering. Pahl/Beitz does not debate on this topic primarily in a separated section. Two main models exist in business management to analyse cost-development-trends: Performance measurement systems (PMS) (Gruening, 2012) on the one hand and indicator systems (Meyer, 2011) on the other. Common to both is the evaluation of a benefit related to prior created indicators. There is a variety of methods existing to evaluate the indicators by dividing both models, such as the balanced score card and the data envelopment analysis for PMS or the Du-Pont scheme as example for indicator systems.

The authors emphasize several recent scientific theses in the specific engineering domains. Important to note is the neglected discussion of early cost-benefit-methods in software engineering by analysing further approaches with such models as point of beginning, e.g. COCOMO (Boehm, 1981) or the function-point-method (Albrecht, 1983). The previously discussed thesis of Kirstan (2011) analyses the cost-benefit of MBE in automotive embedded software engineering via a global study. The conclusion of this work is a process manual for the examination of MBE by costs and benefits, focussing entirely on software engineering. Hampp (2010) evaluates another cost-benefit model in the trial and testing of software functions. Wiese (2012) also focuses on the effort and benefits in optimizing test functions, again in software engineering. Porta (2014) concentrates on automotive electrical engineering and is giving another cost-benefit approach for quality safeguarding measures.

Particularly, the combination of these business management methods for cost-benefit analysis in combination with the work in each engineering discipline is going to build the basis for creating such a model for MBSE in future work. Table 3 finally provides an overview about the previous activities in the development of cost-benefit theories so far.

Table 3. Recent analyzed theories for cost-benefit-analysis in Model-Based Engineering

(X: fulfilled, (X): partly fulfilled, no entry: not fulfilled)

Category/Discipline	Mechanical Engineering	Electrical Engineering	Software Engineering	Business management
PMS				X
Indicator system				X
Hampp (2010)			X	
Kirstan (2011)			X	
Pahl/Beitz (2013)	(X)			
Porta (2014)		X		
Ehrlenspiel (2013)	X			
Wiese (2012)			X	

After analyzing a respective field of recent cost-benefit activities, we identify a lack in research regarding such models on the interdisciplinary system level. The following section is on the one hand dedicated to creating an intial approach for a future cost-benefit model in MBSE and describes on the other hand first research work with regard to MBSE potentials as well as indicators.

4 INITIAL APPROACH FOR A COST-BENEFIT MODEL IN MODEL-BASED SYSTEMS ENGINEERNG

4.1 Design research method

Although a variety of investigations exist, the interdisciplinary system context is missing so far. Regarding this lack in research, we are trying to find a solution via a research hypothesis including the following three research questions in our future work:

- How can identified potentials in terms of indicators for Model-Based Systems Engineering be classified?
- What impacts have those potentials on cost-benefit relationships?
- How can those indicators and impacts be quantified by a model on an interdisciplinary level?

The approach of putting the increasing effort into the early phases of product development is profitable for the series development of products should be answered by these research questions. Particular symbiosis effects between mechanical, electrical, and software engineering perform a key role in future research by creating such a cost-benefit-model for Model-Based Systems Engineering. In order to achieve these goals, one of the authors is involved in recent automotive studies to create such a model. Analyzing industrial processes and the organization structures is one of the main tasks in this context. The consolidation of the current situation in general is completing the descriptive study. In order to do that, an alignment between measurable cost-benefit requirements and founded statements is essential. The decision of which indicators are additionally necessary has to be mainly focused during the development of a model. The development of this cost-benefit model for strategies in Model-Based Systems Engineering and the evaluation of required new indicators in expert interviews as well as in an MBSE pilot project are building next steps. Presumably, it is necessary to combine recent cost-benefit models from section 3 in isolated design disciplines with procedures from business management. Initial point for such a model is the created delta from the current-target-comparison in the particular MBSE pilot project by evaluating the new created MBSE indicators. One of the authors supports the users in such a pilot project during that period and creates thereby a continous current-target-delta. After finishing the MBSE pilot project, the consolidation of the results regarding the pre-post comparison in this project represents the final phase of future research activities. Figure 3 first clarifies an initial methodic approach to answer these questions in the future by visualizing the early research guidance in two parallel worked on packages. The scientific milestones (descriptive and prescriptive study) in this diagram are based on a design research methodology created by Blessing and Chakrabarti (2009).

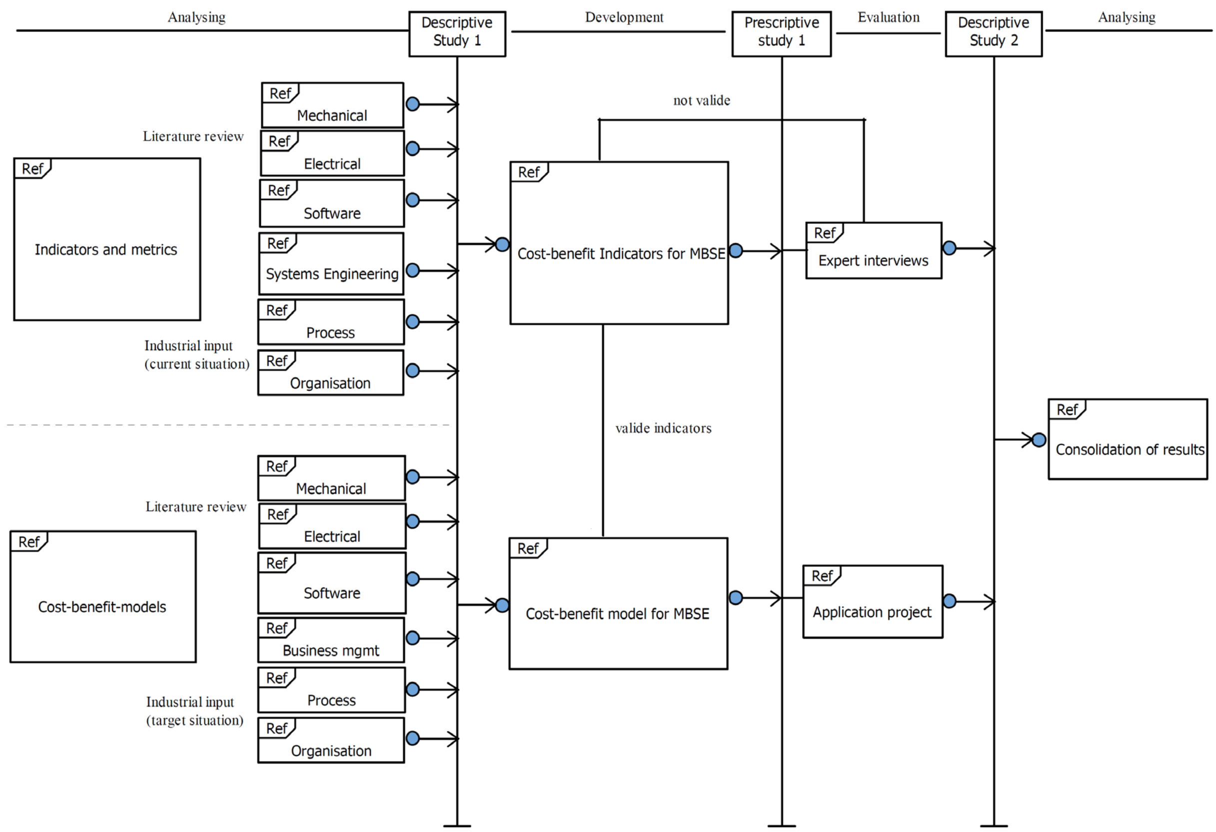

Figure 3. Initial approach for developing a cost-benefit-model for MBSE

4.2 Recent work

In order to achieve these goals, an industrial investigation to identify the demand of new indicators was started. This demand was quantified by expert interviews inside the company. On the one hand, out of eight different research and development areas, structured, verbal interviews were taken from managers. On the other hand established experts at their particular area of work were interviewed to potentials with focus on the system level inside the company. Based on the V-model taken from the VDI-guideline 2206 (VDI, 2004), these expert interviews have first been classified into seven different categories: cross-section processes, specification, modelling, discipline-specific modelling, hybrid tests, physical tests and production. These enhanced categories based on the advanced V-model from the above mentioned figure 2. The category ‘cross-section process’ can be implemented in industry via a System Lifecycle Management (SLM) Backbone. In each category, the taken statements are corresponding either to time, cost or quality based on methodologies in Model-Based Systems Engineering. The recorded statements can be filtered into 120 statements divided by the following categories:

- Cross-section process: 41 statements
- Specification: 38 statements
- Modelling: 24 statements
- Discipline-Specific Modelling: 0 statements
- Hybrid Tests: 4 statements
- Physical Tests: 12 statements
- Production: 1 statement

The focus into the early conceptual phase is thereby recognizable. Especially the category cross-section process is highly represented and underlines the increasing importance of systems thinking. In case for a better understanding of these statements, they were classified into four levels for categorization.The first level provides the category out of the seven product development stages listed below. The second level of a statement helps to divide the recorded statements more specific into detail. Categorizations such as ‘improving quality’ or ‘reduction of development cost’ are examples for this second description level. The third level clusters named potentials given by the experts in terms of delivered sentences and the fourth level describes the abstract meaning of this potential. This abstract description is important for the future scientific isolation from specific company demands with regards either to time, cost or quality. An example for the hierarchic level structure to describe this procedure can be: cross-section process (first level), project management (second level), the integration of project management from vehicle level to system level (third level), cost as abstract categorization (fourth level). All the statements are documented by a mindmap. The transformation from these taken statements to MBSE indicators is realized by an alignment with measurable cost-benefit requirement and the expert potentials. The identification of these requirements is building the next step with regards to the MBSE pilot project. The coherence between the discussed description in the V-model and the ISO 15288 process model should also be highlighted in the future.

5 SUMMARY AND CONCLUSION

This paper first discussed the state of the art in cost-benefit-investigations with regards to the isolated engineering disciplines mechanical, electrical and software engineering. We found out that the evaluation focused on the interdisciplinary system level in the early product development is missing so far. Methods of MBSE deliver an appropriate practice to handle this complexity on system level. An initial approach for the development of such a cost-benefit-model on product system level with recent results for identifying model-based indicators in a company was presented and discussed in a final step. Especially the additional value by the use of MBSE methods should be evaluated and assessed by this approach in the future. How far the increasing tracebility by MBSE methods justifies the increasing effort in the early conceptual phase of new products should also be evaluated by the approach. The necessary symbiosis of formerly isolated engineering domains for an optimized interaction in early development phases should be supported by this resulting cost-benefit-model as well as the evaluation of this model in an industrial MBSE pilot project. Furthermore, the gained results include valid statements to assess the effort in MBSE by the usage of these strategies inside an industrial pilot project.

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