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TOWARDS IMPLEMENTING SYSTEMS ENGINEERING AS PART OF COMMERCIAL VEHICLE DESIGN

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1. Introduction

The competition-induced demand for more efficient, multifunctional and adaptable vehicle systems has significantly increased the need for highly integrated vehicle components. As a result, those mechatronic systems that include an interaction between mechanical, electrical and software-based components have gained in importance [Hellenbrand 2013]. Today, already 90 % of innovations and 30 % of production costs in automotive industry are closely related to mechatronic systems [Czichos 2008]. Current processes in automotive industry often describe a discipline-specific development of system components to handle complexity, which results in an inadequate consideration of the overall system requirements [Schuh et al. 2008]. Efficient integration of mechatronic system design into the overall vehicle development process becomes a decisive competitive advantage [Schaller 2010], [Schöttle 2014].

This paper describes an ongoing research approach to embed systems engineering design into an existing environment of the concept design phase at a commercial vehicle manufacturer to increase the concept quality. The paper starts with a detailed description of the background and context (section 1). In section 2, existing shortcomings in development of high-variant mechatronic systems are discussed to derive requirements for embedding systems engineering design. To verify the derived requirements from an industrial point of view, they were compared with academic requirements derived by academic approaches. In section 3 academic approaches were evaluated according to the derived requirements before the paper is concluded in section 4.

1.1 Background and context: Commercial vehicle design at MAN

MAN is a producer of commercial vehicles, designing, assembling and selling light and heavy trucks, city and long distance buses and components thereof, e.g., engines. MAN is specialised in mass customization for a large number of markets. Thus, MAN vehicles are built for a wide range of applications, e.g., trucks for different uses (e.g., wood transport, military, etc.) and market segments (such as long-haul, distribution or traction).

The vehicle design needs to be highly modular to serve a large portfolio of configurable vehicles (about 10^46 possibilities from a functional point of view) and a comparatively low production volume of approximately 100,000 vehicles per year, with the existing R&D resources [Förg et al. 2014]. The concept development phase in commercial vehicle design often has its focus on planning and determination of variants, definition of standards, modularity and commonality within its product portfolio [Förg et al. 2014].

1.2 Problem description

With the aim to develop only those parts that are needed from a customer´s point of view, the last few years, a product architecture planning process as part of the concept design phase was introduced, [Koppenhagen 2004]. Most product innovations in industry are nowadays realised as system innovations based on multiple components in the field of mechatronics rather than single innovations. The development of product functionalities through mechatronic system solutions will pose a challenge for commercial vehicle manufacturers: the design of interdisciplinary product features and at the same time the enabling of variety by early planning of parts and components within the product architecture and modular kit design is not possible with today`s procedures. Although the architecture planning process was introduced, problems still remain in finding and planning the right parts and components to ensure the cross-component behaviour of a concept. Moreover in this phase, the designer is confronted with discipline-specific as well as interdisciplinary dependencies that are not known yet [Hellenbrand 2013]. This applies on the one hand for technical dependencies of the product and on the other hand for organisational relationships such as common milestones or cross-disciplinary communications [Hellenbrand 2013]. This phase often runs on an intuitive basis within a company, which leads to discipline-specific designed product functionality and system solutions. This problem is reinforced strongly by separated process worlds of the involved disciplines [Reichart 2005] and different development systems for the design of electrical and software compared to mechanical components. A more detailed problem description is part of the research of this paper and will be discussed in section 2.

1.3 Research methodology

The aim of this research, discussed in this paper, is the integration of industrial practice and academic theory in one research approach. Basically, it is found that there are already many academic approaches in the field of systems engineering design, which are frequently not implemented in practice [Stetter 2005]. This finding leads to the assumption that academic approaches often do not address the relevant needs in practice or are not designed for the implementation in an existing development environment. To investigate further, requirements from an industrial perspective, derived from existing shortcomings in development of mechatronic systems, were compared with requirements derived from academic approaches.

To capture shortcomings in development of mechatronic systems, expert interviews and workshops were held with companies regarding their experiences. Here, especially OEMs confronted with similar challenges of a commercial vehicle manufacturer (regarding to their product complexity, quantities, sales markets and their number of employees) were visited. Out of this, requirements were abstracted and classified.

Requirements from an academic point of view were derived from academic approaches. Therefore, an intensive literature review in the field of mechatronic systems engineering design was done. After that, the approaches have been measured against the requirements in order to review the first assumption.

2. Requirements for systems engineering in industry and research

To embed systems engineering design into the existing environment, prevailing shortcomings in developing mechatronic systems at MAN were identified. Moreover, interviews with two companies which are situated in similar niches as MAN, were conducted to get a general problem description (section 2.1). After that, requirements from industrial shortcomings were derived (section 2.2) and examined if these requirements can be substantiated by academic requirements (section 2.3).

2.1 Shortcomings in systems engineering in practice

The interviews took place with two managers of each firm, which were responsible for the introduction of system engineering design and complexity management in the respective firms. The focus of the interviews was mainly on organisational structure, procedural structure and development-related documentation in the concept design phase. Shortcomings within this design phase were discussed, focusing recurring problems and their causes and effects in systems engineering design. In Figure 1 gives an exemplary overview of the discussed questions.

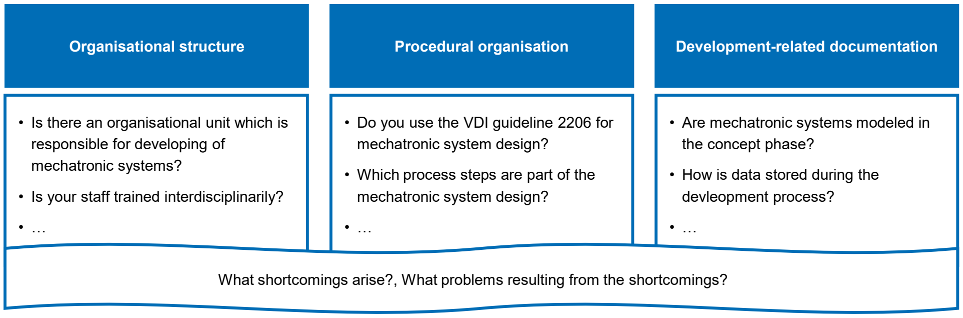

Figure 1. Overview of the interviews questions

Basically, three main shortcomings could be identified (an overview is given in Figure 2):
Shortcomings in organisational structure:
The interviews showed that most companies have a discipline specific organisation with a lack of cross-disciplinary ownership. This company organisation often results in an increased discipline-orientation of employees and particularly leads to a discipline-specific interpretation of requirements of the mechatronic system. Developers often do not know how the development of their component contributes to the overall system and mechatronic interactions are not systematically considered.
Shortcomings in procedural organisation:
A deficit in procedural organisation are discipline-specific processes and procedures within the departments have been established, which are rarely systematically synchronized. This leads to a lack of cross-discipline understanding during the development process of the system to be developed. In addition, often no requirements management on system level takes place, which results in a low traceability of the overall requirement fulfilment during the development process.
Shortcomings in development-related documentation:
Other shortcomings in development of mechatronic systems are the differences in documentation of development-related data and the lack of a common database within the disciplines. This leads to a missing documentation of cross-discipline behaviour. The simulations of overall system behaviour by all disciplines are carried out -if any- in later stages of development. Both, the lack of documentation of cross-component behaviour as well as a missing common database, leads to insufficient data exchange between disciplines.

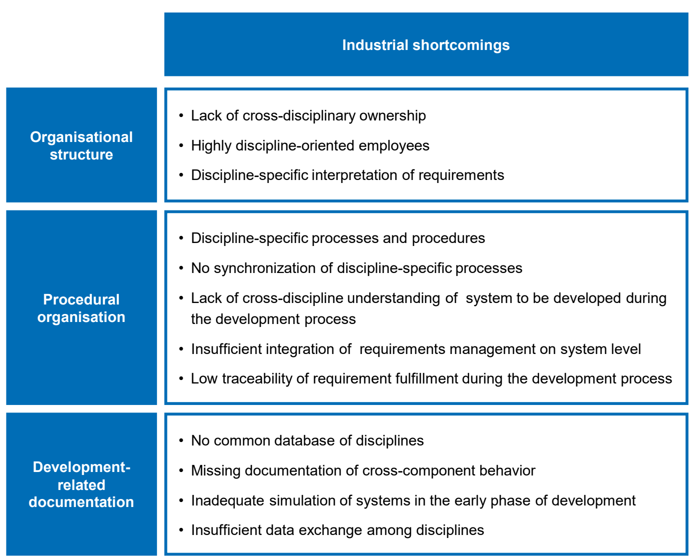

Figure 2. Summary of shortcomings based on surveys

2.2 Identified requirements from an industrial perspective

In general, new products should satisfy increasingly complex demands, which can hardly be met by individual components. Therefore, more and more mechatronic systems are used, which combines knowledge of different disciplines in a single product. Based on the shortcomings described in section 2.1, requirements for embedding systems engineering design into existing development processes can be derived.

Requirements concerning the organisational structure:

Within the organisational structure an interdisciplinary ownership should be established. This ownership should coordinate the comprehensive communication and exchange between disciplines. In addition, this ownership should introduce a common terminology in the development to increase the thinking in terms of systems.

Requirements concerning the procedural organisation:

During the development of mechatronic systems, differently organized disciplines with own methods and development systematics are involved. To synchronize the discipline-specific processes, the development environment should provide a sub-process for the dedicated development of mechatronic systems. Within this sub-process, requirements management on a system-level should be integrated, which is not focused on individual components but whole systems.

Requirements concerning the development-related documentation:

For the dedicated development of mechatronic systems, an interdisciplinary data management should be established, which allows all disciplines to save their development-related documentation. To get a better cross-component understanding of the system an interdisciplinary system design should be integrated into the concept development phase. The result should be a systems concept which is verified by and transparent to all involved disciplines [VDI 2206 2004]. In addition, simulation tools should be integrated into the system design, to identify unwanted interactions between components within a system.

Figure 3 shows an overview of shortcomings in industry and the derived requirements as described in this section.

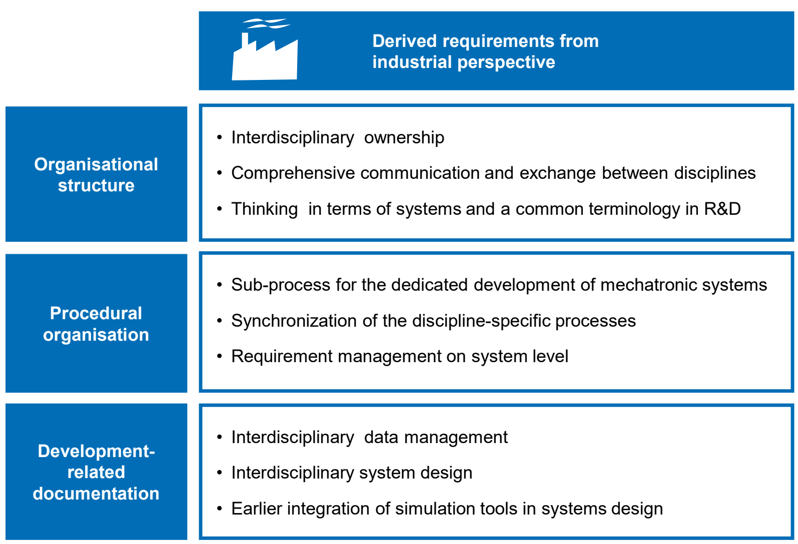

Figure 3. Derived requirements from an industrial point of view

2.3 Identified requirements from an scientific perspective

Due to increasing importance of mechatronics, scientific literature offers a variety of approaches covering the support of mechatronic system development. The approaches are now reviewed regarding the previously derived requirements from an industrial point of view, which is done in Figure 4. On the left side, requirements from an industrial perspective are presented and assigned by requirements from an academic point of view on the right side.

	Derived requirements from industrial perspective	Academic evidence
Organisational structure	Interdisciplinary ownership	▪ responsibles within SE teams have dedicated interdisciplinary tasks [Haberfellner et al. 2012].
	Comprehensive communication and exchange between disciplines	▪ comprehensive communication and exchange between the disciplines should be ensured in order to enable cross-discipline knowledge [VDI 2206] ▪ transdisciplinary collaboration of disciplines in the development of mechatronic systems is necessary [Hellenbrand 2013]
	Thinking in terms of systems and a common terminology in R&D	▪ thinking in terms of systems is necessary for the understanding and design of complex systems [Haberfellner et al. 2012] ▪ a common language for the design phase, which should form the basis of interdisciplinary communication is required [Salminen and Verho 1992].
Procedural organisation	Sub-process for the dedicated development of mechatronic systems	▪ a sup-process to facilitated the necessary collective consideration of functional and design aspects in the development of mechatronic systems is required [Dohmen 2002] ▪ a sub-process to parallelize discipline-specific sub-processes for the development of mechatronic systems is necessary [van Brussel et al. 2001]
	Synchronization of the discipline-specific processes	▪ for mechatronic design an integrated system development is necessary and the discipline-specific processes should be synchronized closely [Hellenbrand 2013]
	Requirement management on system level	▪ a requirements management on system level, based on the cooperation of experts from participating disciplines and an interdisciplinary exchange of informations is required [Haskins 2011]
Development-related documentation	Interdisciplinary data management	▪ the use of interdisciplinary data management is required [Müller 2010] ▪ interdisciplinary and consistent data management is necessary [Damjanovic et al. 2014]
	Interdisciplinary system design	▪ the development of a interdisciplinary system design is required [VDI 2206]
	Earlier integration of simulation tools in systems design	▪ an early integration of simulation tools in the system development process is necessary [Seiffert and Rainer 2008]

Figure 4. Requirements from the industrial point of view supported requirements from the academic point

2.4 Summary

In Section 1.3 the assumption was made that often academic approaches are not considered requirements from industry which result in an inadequate implementation in practice. By comparison of derived requirements from an industrial vs an academic perspective in Figure 4, it can be shown that essential requirements are recognised by academic approaches in the field of systems engineering. As a next step it will be validated if academic approaches fulfil and realise the requirements. To as well address the general objectives of our research, the embedding into existing environment and the handling of complex products are included as a requirement in the assessment of the academic approaches.

3. Existing academic approaches to implement systems engineering

Academic approaches which address the procedural and organisational structure and the development-related documentation have been reviewed. Each approach was analysed regarding the fulfilment of the derived requirements from section 2 by the authors. The range of the criteria for the evaluation is from "fully fulfilled" to "not fulfilled" in total of five grades. The VDI 2206 [2004] describes for example an appropriate process for developing mechatronic systems. This approach fully fulfils the requirement of a sub-process for mechatronic system design. The development of a system is in the foreground but a common terminology in R&D is not addressed, therefore the associated requirement is only hardly fulfilled (see Figure 5).

Approaches focussing the organisational structure:

The process model of [Haberfellner et al. 2012] describes a multidisciplinary approach, which divides the development and implementation of complex systems in individual macro phases. It reflects basically the approach "from rough to detail". First, feasibility studies of a system are made, which are detailed out more and more. During a study a project can be cancelled at any time, if the feasibility is questioned. Once the concept is detailed enough, the development of the system and finally the implementation can be started. Next to the macro model [Haberfellner et al. 2012] describes in a micro model a problem-solving cycle which involves approaches and methods to support the individual macro phases. The approach of [Haberfellner et al. 2012] is a suitable approach for an interdisciplinary design of systems and could also be considered as a possible sub-process. Moreover, [Haberfellner et al. 2012] describes which requirements a project manager of a multidisciplinary project has to fulfil. This description can be used to define an interdisciplinary ownership. The implementation into an existing environment is not subject of his analysis.

[Salminen and Verho 1992] address the active cooperation of different disciplines and the exchange of information in their procedure model. The procedure model is divided into four phases: Planning and concept phase as well as design and drafting phase. Within the planning phase, different product concepts are compared and a list of requirements for a mechatronic system is generated. Then, an interdisciplinary development team searches for solution alternatives, focusing the creativity of the individual disciplines. The approach explicitly considers the synchronization of discipline-specific processes in a mechatronic sup-process. In addition, it is focused on a common language of all disciplines during the development process. Again, indications for embedding into an existing environment are missing.

Approaches focussing the procedural organisation:

The generic method for development of mechatronic systems is defined within the standard [VDI 2206 2004] by the Association of German Engineers with a focus on the early phase of the development process. The approach is based on three main elements: The problem-solving cycle as micro cycle, the V-Model as macro cycle and predefined process modules for processing recurring work steps in the development of mechatronic systems. The micro cycle is based on the generic problem-solving cycle and includes the situation analysis and formulation of objectives and subsequent search for solutions in an iterative process of analysis and synthesis. The V-Model as macro cycle describes the procedures for designing mechatronic systems starting from demands to the final product. The standard [VDI 2206 2004] is an initial frame of a sub-process for mechatronic system development, but insufficiently focuses on requirements management on system level and the early synchronization of all involved disciplines. Additionally indications to embed it into an existing environments are missing.

To tap the potential of an integrated fluid technical mechatronic systems design, [Müller 2010] designed within the BMBF-project Fluidtronic [Schuh et al. 2010] a framework for increasing the effectiveness and efficiency of its design phase. The framework is divided into a defined development process, a functional model for improving the methods used in development and the product information model to strengthen the development process. The approach considers explicitly the organisation of the process and addresses thereby an interdisciplinary system design and requirements management. Müller also describes an interdisciplinary data management but indications for implementation into an existing environment are missing.

The work of [Hellenbrand 2013] focuses on the transdisciplinary planning and synchronization of mechatronic product development processes and describes a process model. The work focuses on process management of mechatronic products. The process model is divided into three main phases: modelling, process planning and process execution. Each of these phases is assigned to individual modules that provide the respective steps and tools. The focus of this approach is on the organisational design of mechatronic development processes. The approach explicitly considers the synchronization of discipline-specific processes. In addition, he describes which tasks an interdisciplinary ownership has to fulfil in a development process. Again, indications for implementation into an existing environment are missing.

[Renner 2007] develops in his work an approach for mechatronic modular kit design using the example of the automotive industry. The approach is designed to handle variety by description of a function-oriented process model. His approach begins with a prioritization of technical parts for identifying modular kit relevant scopes. The subsequent modular kit design process is divided into three phases. In the first phase requirements, relevant functions and assumptions for the development are analysed. Then, solutions and modular kit scenarios are generated and followed by an evaluation in the final phase. After the dedicated modular kit design process, the development is carried out by the disciplines. The focus of the approach is on the procedural description of developing mechatronic systems and gives first indications in controlling of variants and complexity. The approach remains at a very abstract level and not adresses the transferability of the methodology into an existing development processes.

In his procedure model, [Isermann 2008] underlines the need of Simultaneous Engineering in mechatronic system development in order to consider the systems to be developed by the disciplines mechanics and electrics as parts of the overall system. Initially the system is cross-disciplinary defined by the associated requirements and specifications within a sequential procedure model. Subsequently subsystems for the disciplines mechanics, electrics, electronics, control and operation are defined and realized in individual design steps. In the process, mechanical and electrical components are considered as an integrated overall system. Thus, a hardware-oriented and a software-oriented development process emerge per discipline. The two system solutions are integrated after their creation and thence examined as a Concurrent Engineering approach regarding interactions and reliability and adjusted according to demand. The approach is a good frame of a sub-process for mechatronic system development, but insufficiently focuses the early synchronization of all involved disciplines and handling of the development-related documentation. Additionally indications for embedding into an existing environment are missing.

Approaches focussing the development-related documentation:

[Abramovici and Bellalouna 2010] developed a concept for a mechatronic integration platform (mIP) to ensure a multi-disciplinary process and data management based on the V-model of VDI standard 2206. The concept has been designed for implementation into existing heterogeneous PLM systems. The mIP should have cross-disciplinary revisions and release management of product design documents. In addition, a mechatronic meta model, generated out of the partial models of the different disciplines, is supporting the synchronization of the disciplines. The approach considered explicitly an integrated data management, addressing an interdisciplinary system design for synchronizing of discipline-specific processes. In addition, it provides initial indications to embed a common database into an existing development environment. The organisational structure is not considered.

[Hehenberger et al. 2009] introduce a hierarchical design model to support the system design methodology. The aim of the approach is, to compare and increase the reflection of solutions in early phase of development. In addition, the interdisciplinary model should make design decisions comprehensive and create a transparency regarding changes. The discipline-specific system models can be integrated into an overall model, so the specific development systematics of disciplines can be maintained. The approach considers an interdisciplinary system design and is intended to support a common data management. However, he does not addresses the design of the organisational structure and the embedding into an existing development environment.

For methodical support of interdisciplinary system designs the specification technique by [Gausemeier and Deyter 2010] can be used. In applying the frontloading concept, more interdisciplinary system designs should be done according to the set-based concurrent engineering [Lenders 2009] before decisions should be taken. After determination of the final system design, the implementation of subsystems are carried out within the disciplines. The discipline specific processes should be parallelized and synchronized through quality gates and synchronisation loops. The approach explicitly considers the synchronization of discipline-specific processes and an interdisciplinary system design. Indications for implementing into an existing environment as well as the organisational design is missing.

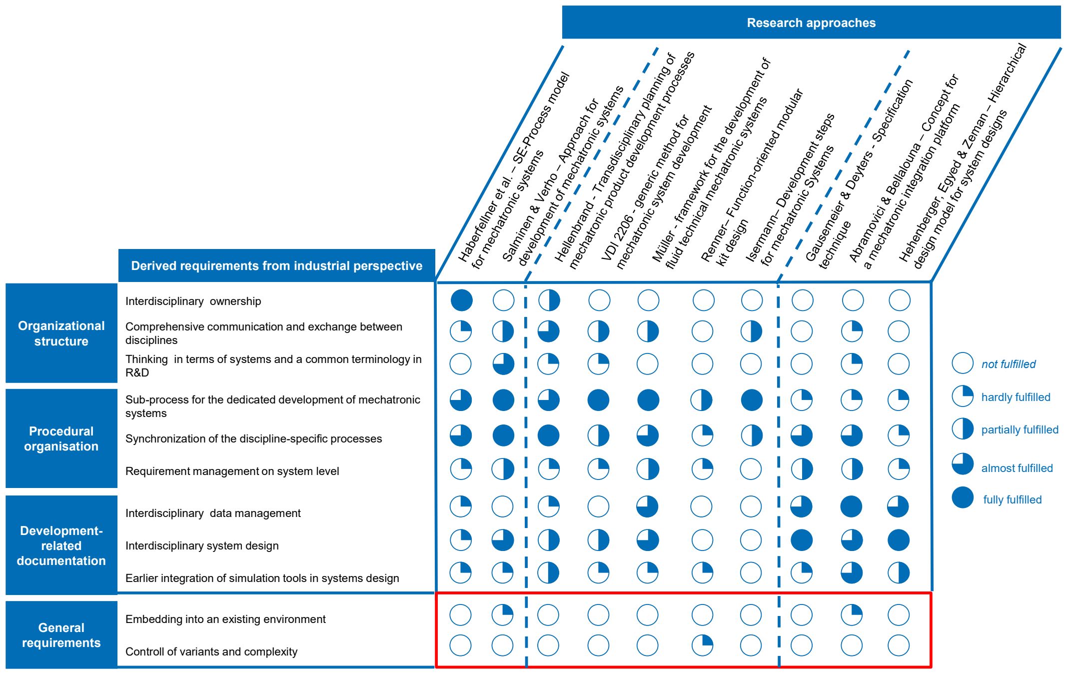

Figure 5. Overview of academic procedural and organisational approaches to implement systems engineering into commercial vehicle design

Most of the approaches have their focus in one of the three requirements categories (organisational structure, procedural organisation or development-related documentation) and none of the development models meets the requirements completely. Additionally, the implementation in an existing development environment is rarely addressed.

4. Conclusion and further work

The development of mechatronic systems in commercial vehicle design has significantly increased in importance. The design of interdisciplinary product features and at the same time the enabling of variety by early planning of parts and components within the product architecture and modular kit design is difficult with today`s procedures. Especially in the concept design phase, shortcomings in mechatronic systems design could be identified and verified by interviews with other companies in the categories of organisational structure, procedural organisation as well as development-related documentation.

In the fields of systems engineering design there are already many academic approaches, which are frequently not implemented in practice [Stetter 2005]. The reason could be, that academic approaches often not address the relevant needs from a practitioner's perspective. To review this assumption, requirements were derived from identified shortcomings in practice and compared with requirements derived by academic approaches (section 2). It can be shown that academic approaches have recognised the needs of practice. If the academic approaches really fulfil these requirements was reviewed in a second step.

Therefore academic approaches in the field of mechatronic systems design were analysed. The classification and evaluation of academic approaches described in section 3 shows that none of the development models meets the requirements completely (see Figure 5). Most of the approaches tend to have their focus in one of the three requirements categories (organisational structure, procedural organisation or development-related documentation). Within these categories the main focus is in fulfilling of individual requirements. Furthermore, the implementation in an existing development environment is rarely addressed.

Thus, further research needs to be done to develop a new method, which can be optimally implemented into an existing development environment. Therefore best theory approaches are used, but best practice approaches have to be considered as well. To analyse the best practice approaches an interview study with focus on organisational and procedural organisation as well as development-related documentation should be done. The approaches found, are examined for their requirement fulfilment as well. In the end, both perspectives - the academic and the industrial - should be combined in one implementable approach.

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