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COMPLEXITY MANAGEMENT DURING THE ANALYSIS OF MECHATRONIC SYSTEMS

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1 Introduction

1.1 Motivation

High market pressure due to the increasing customer requirements in terms of performance (i.e. comfort and security), quality, and price, forces the automotive industry to develop new innovative products at a high quality level. Innovative products demand the synergetic integration of different engineering domains such as mechanics, electronics and information technology being prescribed by the term of mechatronics [1]. The integration of elements of different engineering domains leads to the following advantages [2]:

- Improved price-performance ratios
- Enhanced performance
- Achieved improvements in Behaviour
- Increased functionalities

X-by-wire technologies and active suspension features are two examples for innovative products to improve the security and comfort that are only possible because of the constant interaction of mechanical, electronic and software elements.

However, the automotive industry is actually affected by quality problems in terms of reliability. Evidence is given by the numerous breakdowns due to electronics and the increasing number of call backs (estimation: 1.500.000 in 2004 [3]). These tendencies can be related to the increasing complexity of systems contained in the car (e.g. the vehicle electronic system). However the quality of products, especially of cars, has a growing influence on the purchase decision of customers.

This contribution points out the correlations between mechatronics and quality in terms of reliability and the need to handle the complexity during the analysis of mechatronic systems. Basic theories of complexity management and known analysis methods have been analyzed merged and enhanced to constitute a proceeding model handling the presented requests. The paper concludes with a practical application of the proceeding model in automotive industry and an interpretation of the results.

1.2 Background - system theories

Before introducing the proceeding model linkages between mechatronics and quality in terms of reliability are shown by a short excursus to the system theories.

A system consists of a set of elements, membered due to logic and time linkings. Further more these elements are interconnected by relations [4]. The elements and the relations are known as the structure of a system. Every element and relation is characterized by its properties. Properties are a combination of parameters (e.g. length) and values (e.g. 10mm) [5]. The system structure including the elements, the relations and its properties determine the behaviour of the system. The state of the system is a temporal snap-shot of the behaviour of a system. Consequently a system can be depicted by its elements, its relations and its states.

Engineering systems of interest are usually said to be complex. Unfortunately, there is no single agreement concerning the definition of complexity. However, the generally accepted impacts on complexity [4, 5, 6] are:

- Number of elements and relations
- Diversity of elements and relations
- Number and diversity of states

Considering their impacts on complexity, engineering systems can be structural or behavioural complex [7]. A system is structural complex if it is composed of a high number of elements and relations. Furthermore these elements and relations have to be characterized by large diversity. A system is behavioural complex, if its behaviour is difficult to predict due to the high number of possible states the system can adopt.

By projecting the definition of engineering systems and complexity onto the three major characteristics of mechatronic systems three interdependences can be found:

- Interdisciplinarity leads to higher diversity of elements and relations and has an increasing impact on the structural complexity.
- The high degree of cross-linkings in mechatronic systems are on par with a high number of relations, which leads to an increasing structural complexity too.
- The flexibility in terms of the increasing functionalities leads to elevated number of states of a system and increases the behavioural complexity.

As a conclusion, mechatronics lead to an elevated degree of complexity due to large diversity and the high number of relations and states. Therefore, the prediction, description and management of the behaviour of mechatronic systems pose high demands on the analysis of these systems. However, the necessity of a profound knowledge of the structure and the dynamics of a system is eminent in order to predict the behaviour of a system and to develop reliable products. Regarding Luhmanns “supposition“, based on “Cope’s Rule“ from the theory of evolution and the projection of this theory on technical systems [8], the complexity of these systems progresses evolutionary. As a consequence, a profound knowledge of the actual system leads to a better estimation of the performance of future systems too. Reducing the systems complexity is not a suitable approach, because of the loss of flexibility to react fast on market changes or customer requirements [9].

Consequently, the objective is managing the complexity during the analysis of mechatronic systems in order to predict the system behaviour in an appropriate way and to gain better estimation of the performance of future systems.

2 Method

To address this problem, a proceeding model has been derived from existing system analysis approaches, adapting steps to the problem and developing self-reliance by extending the existing models at hand to the most opportune level.

Preliminary, elementary principles have been considered, comparing and discussing diverse approaches dealing with complexity and analysis. Taking those principles into account, the introduced proceeding model is designed especially for analysing systems whose nature is mostly affected by complexity and heterogeneity. With regard to other scientific domains, proceeding models and principles developed from a non-technical perspective have also been included. By taking different considerations into account, the developed proceeding model is trimmed to fit the demands of mechatronic systems of automotive industry most accurately.

2.1 Principles for complexity management

Principles are fundamental, universally valid and abstract. Developed from experience and cognition, they constitute the theoretical basis for any form of actions [10]. In the following, principles derived from the object oriented analysis method extended by social sciences have been transferred onto mechatronic systems, evaluating promising benefits. As methods are more specific, designed to fit a certain situation or phase, thus setting the framework and rules for actions [5] they will be discussed in brief, following the abstract principles. In continuation, the proceeding for the analysis of a system is defined in consideration of the principles and methods managing complexity.

As in many other fields, the technical definition of the principle of *abstraction* implies concentrating on essential and omitting un-essential entities of a system. The well-established black-box is representative for the application of the principle [11, 12]

Selectivity, as a part of the process of abstracting, implies the risk of declaring un-essential entities, essential and vice versa. As a principle, selectivity demands consideration and compensation of this risk [3].

The enclosure of objects, both changeable and of static character is prescribed as *information hiding* (encapsulation) and aims at the definition of subsystems and narrow interfaces. Dynamic considerations are uncoupled from the static view and thus allow reducing number and variety of elements under examination [12]

The occurrence of hierarchical system structures as ranking of abstractions depends on the viewed system *(hierarchy)*. Hierarchical structures are present in organizational systems as communicational and command structures and in technical systems as component or functional hierarchies of objects and classes [8,11].

The principle of *association* implies the interrelation of comparable circumstances, for example chronological or physical [12]. According to the definition, inheritance and hierarchization of classes are closely related and inevitable for the successful appliance of the principle of association.

The principle of *scale* allows surveying a complex system, combining the three sided dependency of whole, parts and viewer of the system. The differentiation between modelling and proceeding of analysis allow navigating through a highly complex model by the choice of different levels of abstraction [12].

Categorizing the behaviour of system elements, the definition of categories of behaviour is based upon the hierarchization of objects and classes. Therefore, the behaviour of a system element is composed of behaviour due to immediate causation (i.e. level of objects) and behaviour due to similarity of functions (level of classes) [12]. As categories of behaviour focus on system performance, managing of dynamic complexity is achieved by standardizing behaviour of classes of objects.

The pervading methods of organization are prescribed as being essential for system analysis [12], providing most detailed insight into a system. Being more similar to a method than a principle, pervading methods of organization are closely related to principles, due to their shortness and general validity. The following three steps are implied by the pervading methods of organization:

- Objects and attributes
- Whole and parts
- Classes, objects and their differentiation

2.2 Existent proceeding models

Consisting of numerous steps, transition from principles to proceeding models is fluent, which leads to the survey of proceedings. Implementing the principles managing complexity, a proceeding is defined, forming a methodology in association to generating a product model. As a basis, proceedings for system analysis have been taken into consideration, divided into single steps and rearranged to fit the demands of mechatronic systems. Focussing on complex systems, the implementation of principles managing complexity and supporting modelling methods have been considered and adapted to the steps of the proceeding model.

Proceeding models taken into consideration [13, 14, 15] are presented in brief in the following, combined and developed to a proceeding model implying the analysis and modelling of complex systems.

Decomposition in three steps by Pimmler & Eppinger [13] consists of identifying functional and physical elements in the first step, secondly defining interrelations of elements. As last step, chunks of elements are developed on basis of their interrelations. Visualization of the system and chunks of elements are realized by application of interaction matrices, differentiating between categories of interaction and weighting interactions. According to the method, conflictive pairings of elements can be documented in the matrix by weighing them. Chunks are not representing strictly functional or physical dependencies, but grouping elements under influence, positive or negative.

Applying the method onto complex mechatronic systems of a car, the effort of implementation has to be taken in consideration. Potential lies within the identification of changes' impacts to the system and the definition of subsystems.

A method developed by Rajan [14] for the analysis of control systems consists of four steps: the collection of information, functional modelling of subsystems, grouping of functional subsystems and the model's verification according to the requirements. More detailed steps of this proceeding [14] are neglected in this paper, enabling adaptation of the method onto mechatronic systems in general and therefore leaving more scope for the user.

Developing a method for the analysis of engineering products, Pahl & Beitz [15] describes the proceeding of analysis as the process of abstraction, structural analysis and detail-analysis of a system. Being the most general approach in system analysis, the proceeding of [15] must not be prescribed in detail, but should be taken into consideration when defining a proceeding model for mechatronic systems, due to its generality.

Starting with the abstraction of the system and, more general, the collection of information, the described proceedings for system analysis have several common properties. Differences, however, lie for example within the grouping of subsystems under functional or structural aspects. Same as the collection of information, the grouping of subsystems depends on the expected outcome of the analysis. Structural groupings support the definition of a system's degree of freedom, while functional groupings in contrast enable function combination or separation of system elements. It is obvious, that different proceedings contribute to achieve different benefits, whose combination enables the holistic analysis of a complex mechatronic system aimed at in this paper. In the following, a proceeding model is presented, developed from the discussed proceedings and embedding modelling methods and principles for the analysis of complex mechatronic systems.

2.3 Proceeding model to manage the complexity during the analysis of mechatronic systems

Prior to the definition of a proceeding model, the principles of managing complexity are assigned to numerous modelling methods, which in turn are assigned to the steps of the proceeding model, representing a holistic approach for system analysis and modelling. Providing a basis documenting the proceeding, supporting the data collection and advancement by adding principles and structuring information, the attending of the procedure by product models is inevitable. Therefore, numerous modelling approaches were taken into consideration, reviewing their interaction with principles managing complexity and ability to support the steps of the proceeding model (figure 1). As mentioned above, *the pervading methods of organization* being more similar to a method than a principle have been considered as methods.

		Methods						
		Functional Structure	FAST-Model	Effect Strucutre	Design Structure Matrix	TIPS	Structure Graph	Pervading Methods of Organization
complexity	abstraction	x	x	x	x	x	x	x
	selectivity	x		x	x	x	x	
	information hiding				x			
	hierachy			x			x	
	inheritance							x
	association							x
	scale	x			x		x	
	categorizing the behaviour							x
proceeding model	objectives	x	x			x		
	objects and classes				x		x	x
	modelling	x	x	x	x	x	x	
	grouping				x		x	x
	verification	x	x	x	x	x		
	analysis	x	x		x		x	x

Figure 1. Interaction of methods with principles managing complexity and the steps of the proceeding model

Being a side-product, the supporting model needs to fulfil the criteria of being target-oriented and furthermore implemented with as little effort as possible. Necessarily, chosen models need to interdigitate closely.

Considering the analysis of a complex mechatronic system, first step of the proceeding model (figure 2) *(objectives)* must be the definition of requirements and information demand, implying the identification of elements and relations of a system and dealing with the outstanding properties of a mechatronic system, namely the closely related disciplines. Aiming at understanding and modelling a system, methods of functional modelling are suggested for that step, as shown in the case study.

Second step of the proceeding *(objects and classes)* being the collection and structuring of the system's elements in terms of objects and classes according to the defined requirements in the first step, tabular modelling methods prove to be the alternative to be chosen. Supporting understanding and interpretation of abstract tabular data structures, functional and structural hierarchical structures of classes can be added, representing mechatronic disciplines or functions in particular.

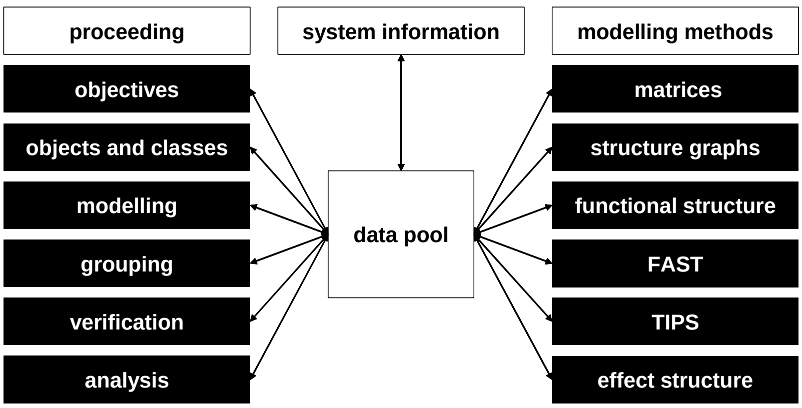

Figure 2. Proceeding model for the analysis of complex mechatronic systems

As a third step *(modelling)*, the system is modelled, preparing the collected information descriptively and therefore implying different modelling notations chosen from the mentioned possibilities. Besides matrices, the functional structure, functional analysis system technique, and structure graphs are considered to support the modelling of the system, the FAST-model (Functional Analysis System Technique) forming the interrelation between functional and structural view. Additionally, effect structures according to TIPS (Theory of Inventive Problem Solving) add aspects of harmful functions on the one hand and physical insights on the other. Prescribed notations are considered to found on the same informational basis, offering the possibility to easily transfer the system from one notation to another.

Being of great importance for analysis, the *grouping* (step 4) of elements allows the consideration of outlined sub-systems, sub-functions or classes of the analysed system. Intensely affecting the grouping, the precedent steps are vital and closely related to each other. As the transitions between the steps “objects and classes” to “modelling” and “grouping” are fluent, the proceeding, especially the mentioned steps, is considered being optionally iterative, illustrated by the following case study. To accomplish the grouping of elements, the application of matrices is apparent, providing numerous automatisms supporting the grouping of elements [16]. Unfortunately, different views demand different matrices, which cause loss of the holistic approach. To achieve relief, insights attained by application of matrices can be lead back to the more descriptive product model, restructuring and extending the notation.

Verification (step 5) of the identified potential of optimization is carried out by transferring perceptions onto the system in reality and measuring effort and benefit of the implementation. Hence, this step can only be accomplished in support of the specialist departments in responsibility of the considered subsystem.

Final *analysis* (step 6) implies conclusions based on previous steps of the proceeding and, stressing the holistic aspect, consolidating the sub-systems on basis of defined objects and classes. Being dependent on definition of objectives and actual circumstances, conclusions to draw are not depicted in particular at this point, but being exemplary pointed out in context of the case study in the following chapter.

3 Practical application of the proceeding model

The object of the case study to evaluate the proceeding model has been an upper class car containing a high number of technical and functional features leading to high diversity and large number of elements and relations. The case study focuses on a complete energy assessment. The general proceeding of the analysis is shown in figure 3 and will be explained step by step.

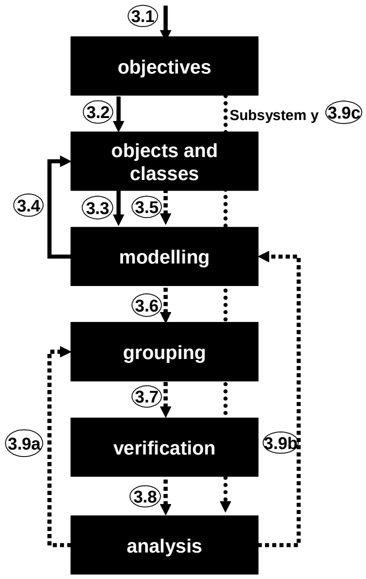

Figure 3. Proceeding during the practical application

3.1 Objectives

The first step aims at the definition of objectives for the project. Regarding three major objectives concerning the topic energy, the following target system has been worked out by the team:

- The cognition of the system with its subsystems, elements and relations is necessary in order to get a common understanding of the system behaviour.
- The identification of critical elements requires a definition of “critical” depending on the three major objectives related to energy. Based on this definition criteria have to be worked out in order to select only the relevant sub-systems, elements or states for further investigations.
- The identification of optimization potential supports the selection of relevant matters or the assignment of priorities to work out optimization concepts.
- Realizing the generated options to optimize selected subsystems, elements and relations structural and behavioural consequences for the overall system have to be taken into account.

Further more this step deals with the gathering of information considering the structure and the properties of the subsystems, elements and relations. In this special case helpful sources of information have been performance specifications, requirement specifications, documentation for industrial training and before all databases of test results and discussions with experts.

3.2 Object and classes

Regarding the objective “system cognition”, the team consisting of members of different disciplines, has decided to gain a common understanding of the basic energetic interdependences in the car. To develop an abstract product model, only three objects have been defined: subsystems, relations and states. As the focus of the analysis lies on energetic considerations the classes are: mechanic, electric and thermic. Additionally, “information” has also been considered a class.

3.3 Modelling

For the modelling, a functional structure [17] has been chosen, because the flow of the different forms of energy constituted the skeletal structure of the considerations. The developed model is shown in figure 4. It is composed of states (circles), directed energy flows as relations (arrowed lines) and subsystems (rectangles) that describe functional units of the car. Colours represent the different energy forms. In order to preserve the clearness of the model only the major energy flows have been taken into account. Additionally, only states regarding the system boundary are illustrated in the model. Besides common understanding of the system behaviour, the following conclusions have been drawn:

- Subsystem (7) occupies a central position in the system, due to the high number of relations. However the diversity of the relations is low, so that the subsystem isn't preliminary taken into account for further investigations.
- Subsystem (2) is characterized by a high number and diversity of relations and is one of the most important functional units.
- Last but not least subsystem (9) stands out too due to the high number and diversity of relations. Further more it constitutes an important interface to the customer.

The level of abstraction of the functional model doesn't allow any propositions for optimization potential; however its development led to common understanding among team members and gave the possibility to select two subsystems for further investigations in this early stage of the project. The following steps concentrate on the analysis of subsystem (9).

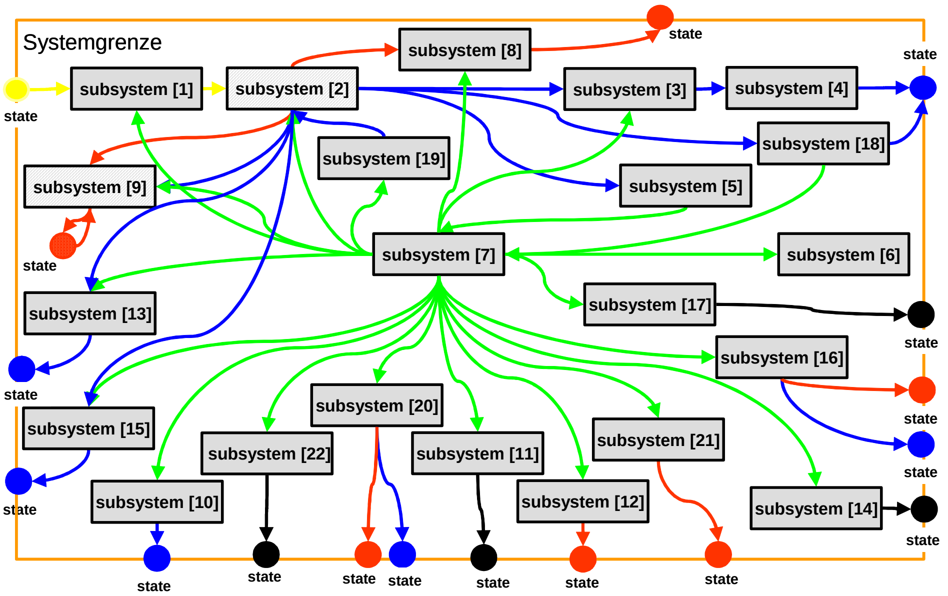

Figure 4. Functional structure of the car

3.4 Object and classes of subsystem (9)

The proceeding starts again with defining objects and classes, as overall objectives experienced no change. However, the new degree of detailing involves the definition of new objects and classes. Elements (synonymously used to components) and relations have been considered as objects. Furthermore, the following classes of elements have been taken into account: transducers, energy store, consumer, conductor, sensor, control units. Additionally three classes of relations have been defined: energy, signal, and material.

3.5 Modelling of subsystem (9)

In order to get a profound knowledge of the system structure, a DSM (Design structure Matrix) has been set up. Therefore, all energetically relevant elements have been collected, allocated to the different classes and their relations documented in the matrix (1) shown in figure 5.

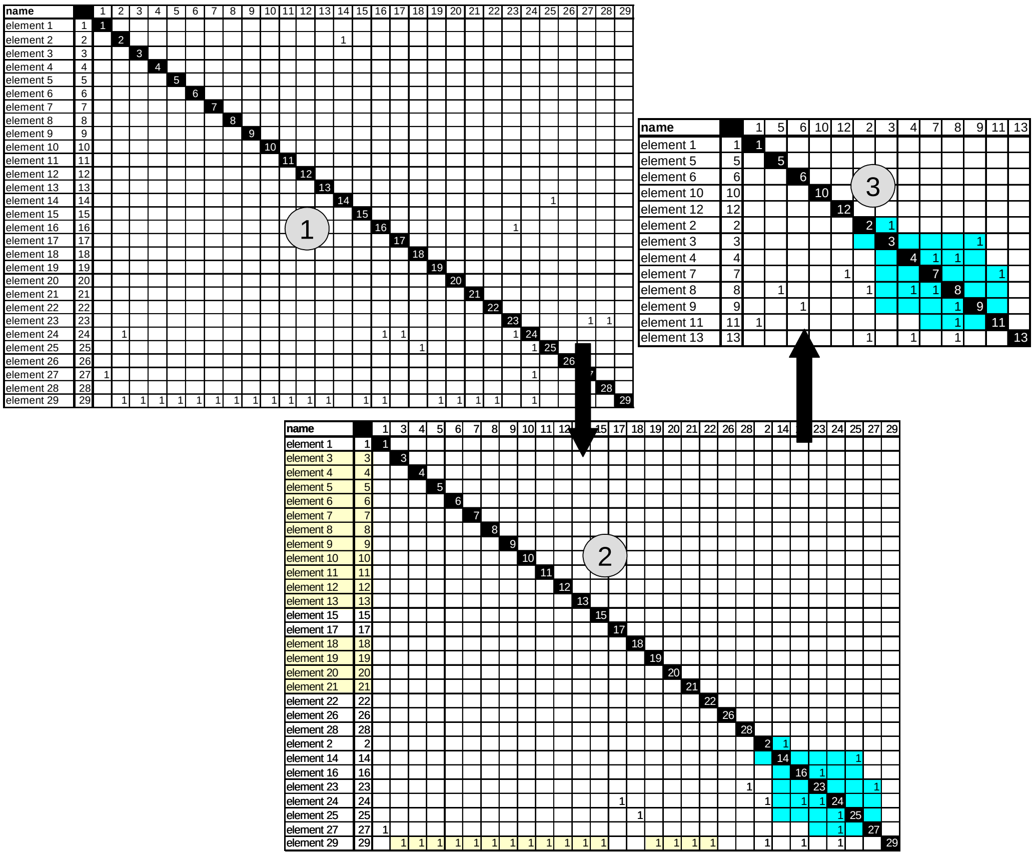

Figure 5. DSM's of subsystem [9]

3.6 Grouping

Applying the well known procedure of partitioning onto the introduced matrix (1) (figure 5), unavoidable feedback loops due to the circular flow of material through the system become obvious in the second matrix (2). Thus, the related elements need to be considered as a sub-system, inseparably connected through closed loops and therefore to be optimized as a whole. The second cognition made on basis of the introduced matrix is the identification of element 29 as a bus-system. Characteristic for such bus-systems are the numerous elements interlinking with the bus-element. Apparently, each interlinking element possesses one strictly unidirectional and exclusive relation to the bus-element, and therefore is encapsulated in terms of information hiding in matrix (3), where element 29 reappears as element 13, now implying the hidden elements which have no further influence. This way, the number of elements under consideration has been reduced about more than 50%, supporting management of complexity.

3.7 Verification

Verification of the achieved outcomes has been carried out in cooperation with specialists, evaluating the relevance of neglected elements and approving the reduced version of the model. In future, verification has to be systematized and supported by simulation – development of a simulation model is in progress, thus being more efficient and time-saving.

3.8 Analysis

The last step of the proceeding prescribes the interpretation of achieved results concerning functional and structural aspects as well as the defined classes and objects. To achieve an outcome matching the holistic claims of the research, the introduced proceeding has to be performed on other sub-systems, thus enabling the application of the principles of association and hierarchization onto the whole product. The character of the proceeding implies the iterative performance, widening the scope for the user to adapt the degree of abstraction to the actual optimization process. In case of the example depicted above, the linking elements between the clusters were taken into consideration and analyzed in detail, bringing forth innovative strategies for the whole subsystem in terms of integration of functions and parts.

3.9 Further considerations

Within the scope of the cooperation the presented results are only a snap-shot of the overall findings up to this point. Therefore the description of the practical application of the proceeding model closes with some examples for the further action

The identified cluster arising from the partitioning and the encapsulation of the DSM has been the object for further investigation. The elaboration (step: 3.9a) of the interdependences between the elements regarding subsystem (9) and the subsystem (functional units) of the car have been illustrated in a second DSM. The partitioning of this DSM has helped to identify the main relations.

Furthermore, the generation of optimization options (step 3.9b) has been focused on the identified cluster of subsystem (9). Adopting TIPS by combining useful and harmful functions has helped to identify and solve new sub-problems. Regarding the cognitions due the refeeding of subsystem (9) in the overall system, the structurally and behaviourally impacts of the generated concepts on the system could be estimated in appropriate ways.

The functional structure (section 3.3) has revealed a second critical subsystem due to the high number and diversity of relations. This subsystem passed through the proceeding model in a similar way. The analogue definition of objects and classes for the elements and relations of subsystem (9) and subsystem (2) permitted the comparison of the two subsystems (step: 3.9c). Questions like “are there any comparable classes” or „are there comparable functional chains“ in combination with research regarding criteria like costs, energetic characteristics, boundary conditions etc. have helped to identify optimization potential at the same time as optimization options.

4 Conclusion and outlook

Mechatronics offer high potential for successful products, but impose at the same time special requirements on the analysis of these systems due the increased level of complexity. In order to gain profound knowledge of the system structure and behaviour on the one hand and to manage the complexity on the other hand, the merge of basic principles derived from the object oriented analysis, analysis methods and proceedings leads to the presented proceeding model. The object of the evaluation has been an upper class car. Intermediate results are:

Referring to the main project objectives regarding the energetic system behaviour and the developed target system, the presented proceeding model has supported the team to select only the relevant subsystems or elements for further investigation. Thus, the complexity has been handled. Furthermore, the combined application of different modelling methods (TIPS, DSM, etc.) handled the requirements occurring due to the interdisciplinarity, opened new viewpoints on the problem and led to new cognitions. The proceeding allows the situational application of modelling methods adapted to the degree of abstraction (e.g. functional structure vs. DSM). According to the overall project objectives, it was possible to identify optimization potential and generate optimization options not only for elements, but for the overall system. Detailing and evaluation of the developed concepts are ongoing.

However some critical aspects about the presented proceeding have to be mentioned:

- The quality of the results is strongly influenced by the quality of the input information. E.g. the information in the databases has often been acquired under different boundary conditions, so that the interpretation is difficult. Future work includes restructuring and the refilling (e.g. carry out tests) of the database in order to improve the provided information and to achieve new cognitions.
- The presented proceeding is time consuming due to information gathering and use of different analysis methods. E.g. the DSM of subsystem (9) has been build up in cooperation with experts during a one day workshop. However, time is precious and an optimization of the proceeding is necessary. The restructuring of databases contributes to a more efficient proceeding. Furthermore the enquiry for automated tools for analysis of systems (e.g. MOFLEPS [18]) is ongoing. An evaluation regarding the applicability of the tools is planned.

Resuming the optimization of mechatronics can only be reached due to a profound knowledge of the system structure and behaviour. The presented proceeding constitutes a first approach which led to positive results. However, the quality of the input information has to be ensured and the time consuming proceeding needs to be optimized.

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