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USING DSM FOR THE MODULARIZATION OF SELF-OPTIMIZING SYSTEMS

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Keywords: product structuring, self-optimization, development process, specification techniques

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1 FROM MECHATRONICS TO SELF-OPTIMIZATION

Nowadays, most mechanical engineering products already rely on the close interaction of mechanics, electronics, control engineering and software engineering which is aptly expressed by the term mechatronics. Future mechanical engineering systems will consist of configurations of system elements with inherent partial intelligence. The behavior of the overall system is characterized by the communication and cooperation between these intelligent system elements. Self-optimizing systems are able to react autonomously and flexibly to changing environmental conditions. They are capable of learning and optimizing their behavior in run-time [1].

Within the Collaborative Research Center 614 "Self-Optimizing Concepts and Structures in Mechanical Engineering" one demonstration system for self-optimization was realized on a scale of 1:2.5. It is the innovative rail technology "Neue Bahntechnik Paderborn/RailCab". The core of the system comprises autonomous vehicles (shuttles) for transporting passengers and goods according to individual demands rather than a timetable. The shuttles are modular constructed from standardized intelligent elements.

A so called self-optimizing process is repeatedly carried out: 1) The system elements collect information about the environment of the shuttle and its state and exchange them. 2) They determine objectives for the optimization of the behavior of the shuttle. 3) Based on these objectives the behavior of the shuttle is adapted. That is achieved by adapting the parameters and where necessary the structure of the system. The term parameter adaptation means adapting a system parameter, for instance changing a control parameter. Structure adaptations affect the arrangement of the system elements and their relationships.

The RailCab shuttle is used to exemplify the methods presented in this contribution.

2 DEVELOPMENT OF SELF-OPTIMIZING SYSTEMS

A new powerful paradigm such as self-optimization naturally calls for new development methods and tools. Self-optimizing systems exhibit an increasing complexity and therewith more interdependencies: The behavior of the system is determined by the interaction of its intelligent system elements, which reconfigure the system and therefore adapt its behavior. Several aspects related to self-optimization have to be taken into account during the development process. One possibility to meet this challenge of complexity is product-structuring [2].

The product structure is worked out during the initial development phases "planning and clarifying the task" and "conceptual design". It influences important technical aspects of the product (i.e. reliability, reuse of standard components, etc.) and the following domain specific development phases. The result of the initial phases is the principle solution of the system which describes its general structure and mode of operation. We have developed an approach of how to create and how to describe the principal solution of self-optimizing systems and, based on this description, how to structure them. This approach is also applicable on mechatronic systems, because self-optimizing systems base on mechatronics.

The classic development methodology has been enhanced by some essential steps [3]. In the first phase "planning and clarifying the task" we start with identifying the core task of the system. Afterwards we analyze the environment to identify the essential constraints and influences affecting the system. Furthermore we are able to define characteristic couplings of situations (consistent

combinations of influences) and system states. These couplings are called application scenarios and focus on subsets of the system functionality. The results from the initial phase are summarized and recorded as the requirements.
In the second phase "conceptual design" we formulate solutions for these defined application scenarios. The developed solutions are validated and the best ones are consolidated to a principle solution. Then we analyze whether there are contradictions in the principle solution which can be solved by self-optimization. For these identified contradictions we define self-optimizing concepts including the three steps of the self-optimizing process. Therefore we structure the system into modules which could be seen as autonomous system elements. We use three methods for the product structuring which will be explained in the following chapter. The evaluation of the principle solution according to technical and economical criteria forms the end of this phase.
During this conceptual design phase all results are described with a set of semiformal specification techniques [3]. The set consists of different views on the self-optimizing system. Each view is mapped by computer onto a partial model. The main views respectively partial models are: application scenarios, functions, objectives, active structure, shape and behavior. This last view is considered a group because there are various types of behavior (e.g. the logic behavior, the dynamic behavior of a multibody system, the cooperation behavior of system elements etc.). There are also relationships between the partial models, leading to a coherent system of partial models that represents the principle solution of a self-optimizing system.

3 PRODUCT STRUCTURING

As already mentioned one key aspect to handle the complexity of self-optimizing systems is product structuring. The aim is to subdivide the system in hierarchical structured modules and system elements that can be developed in parallel. For the structuring during the conceptual design phase we use three methods [4].

1. To analyse the interdependences between the system elements for each application scenario we use the Design Structure Matrix [5]. Different kinds of interdependences, for instance spatial aspects, material, energy and information flows, are analyzed to structure the system in a hierarchical way.
2. Besides this basically flow-oriented analysis of the system we use the Module Indication Matrix to analyse the characteristics of the system elements [6]. Aspects that are taken into account are for example the functionality that is fulfilled by a system element, used materials or maintenance rates.
3. Additionally the Design Structure Matrix was modified to examine the reconfiguration of autonomous system elements. The method is the so called Reconfiguration Structure Matrix. It is used to examine which structuring arises from the different configurations of the system. A result for example could be a basis module with additional activated add-on modules for each operating mode of the system. Figure 1 shows the application of the Reconfiguration Structure Matrix with the superposition of application scenarios in the context of the product structuring process.

The results of all three methods are evaluated and an adequate product structure is chosen. The resulting modules are as far as possible autonomous and can be developed in parallel. This modular structured systems offer the possibility to reuse system elements over several product classes and generations. From the point of view of information technology the closed modules offer the possibility to encourage them with initial partial intelligence and to realize reconfiguration.

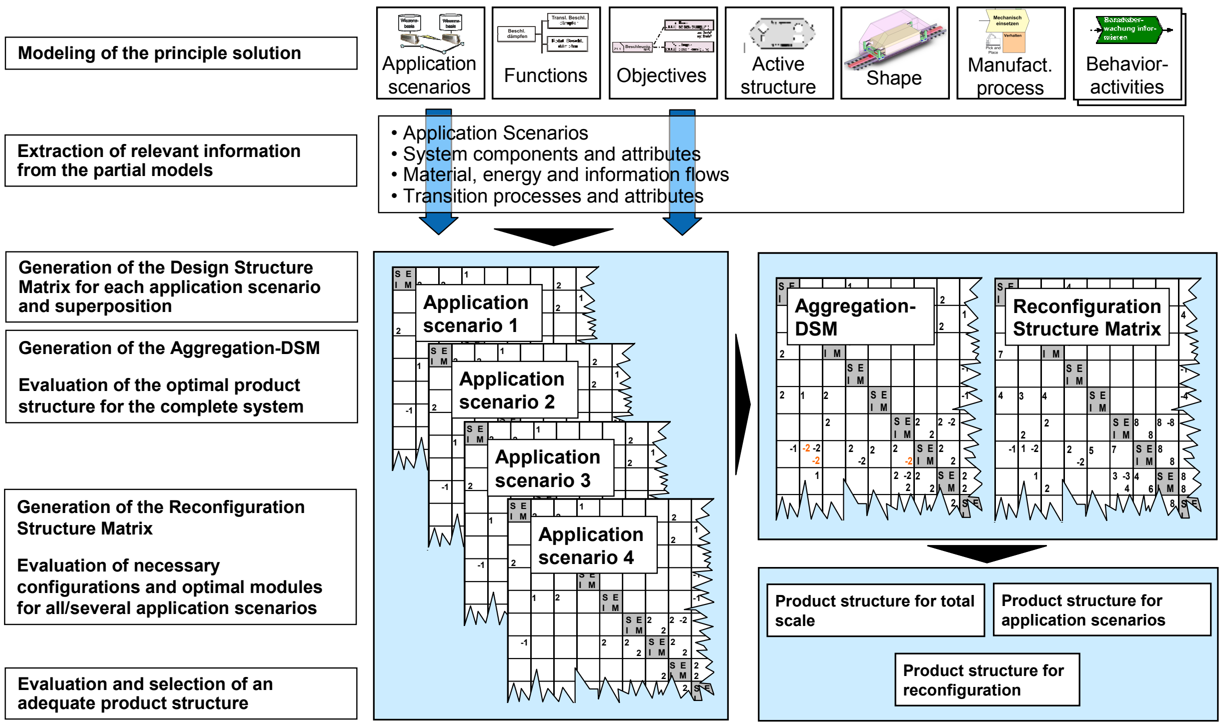

Figure 1: Analysis of application scenarios for reconfigurable systems

3 CONCLUSIONS

Product structuring is an important step in the development process for modern mechatronic and self-optimizing systems. It helps to reduce the complexity and to increase the carry-over of system elements and modules as well as the system reliability. On the other hand, it requires additional effort. A success factor is the seamless integration in the development process, by using established specifications, methods and tools. The presented approach shows, how this could be realized for tomorrow's mechanical engineering systems with a high share of information technology. The additional effort for product structuring is it worth, compared to typically sub-optimal interfaces and high synchronization efforts during development.

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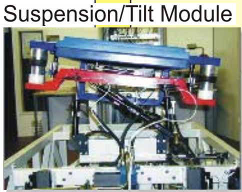
Self-Optimizing Systems

Influences on the Technical System

Surrounding	User	System
e.g. Uneveness of track-profile	e.g. changed usage mode	e.g. wear and tear

Shuttle

Suspension/Tilt Module



System of Objectives (Internal objectives)

Behavior — Mathematical symbolic description of the behavior

Structure — Representation of physical / topological structure

Parameters — m:= 10, c := 15 — Instruction-based processing using data description

Technical System (e.g. Shuttle, Suspension / Tilt Module)

Actions of the self-optimization process:

1) ***Analyzing the current situation***
2) ***Determining the system of objectives***
3) ***Adapting the system behavior***

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Challenges for Product Development

Increasing product functionality	Numerous variants	Shortened innovation cycles

Resulting challenges for the development of future mechatronic products

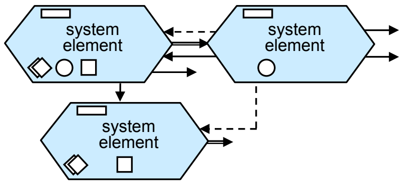
- Autonomy by inherent partial intelligence (Self-Optimization)
- New paradigm of information processing
- Ability of adaptation by reconfigurable structures

→ **Increasing complexity of the system by many interdependencies that need to be taken into account during the development process**

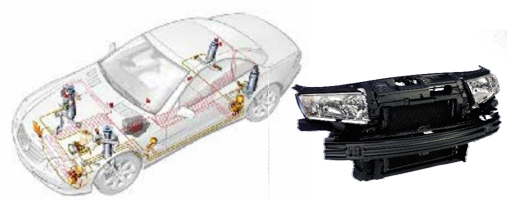
Method of resolution for the product development

Reduction of complexity by modularisation of the product into almost independent modules

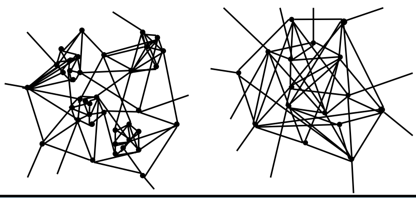
Aspects of Product Structuring



Different aspects of interdependencies have to be taken into account :
- Flows (material, energy, information)
- Spatial interdependencies
- Properties of system elements



Contradictory interdependencies have to be adjusted:
- Function orientated product structure
- Shape orientated product structure



In order of different development tasks two oppositional types of product structures are possible:
- Modular product structure
- Integral product structure

The objective is a hierarchical product structure that encompasses all relevant aspects of interdependencies and that balances this aspects against each other.

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Method for Modularisation

What is needed to structure complex mechatronic and self-optimizing systems?

- Catalogue of basic development tasks and design rules for product structuring
- Detailed specification of the product concept
- Methods and tools for product structuring
- Phase model

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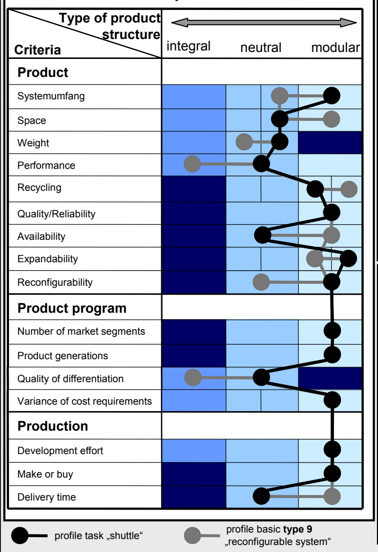
Basic Development Tasks and Design Rules

1. Miniaturized product
2. Cost optimized mass product
3. Performance optimized single product
4. Complex miniaturized system
5. Repetition part (numerous variants)
6. Complex system with specialized modules
7. Mechatronic function module
8. Safety-sensitive system
9. Reconfigurable system

Basic type 9: reconfigurable system



Constraints

Autonomous vehicle
- High complexity
- Status: prototype S 1:2,5
- Test system for innovative control and communication strategies
- High importance of safeness and reliability
- Expandability
- Low costs (standard parts, multiple use)

Design rules

Product Structuring according to:
- Reutilisation
- Development risk
- Durability
- Available space
- Maintainability
- Reconfigurability
- …

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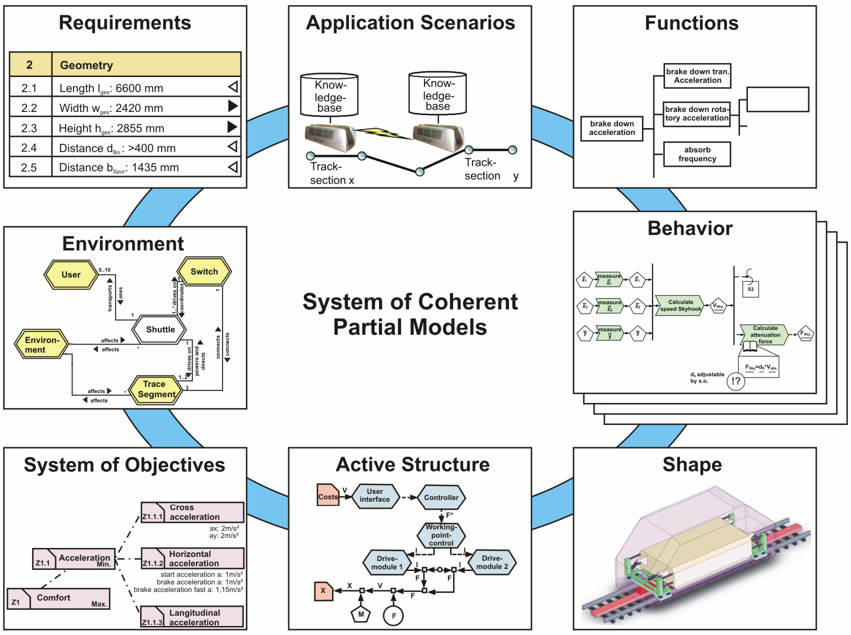
Detailed Specification of the Product Concept



The specification of the product concept is a necessary basis for product structuring. It includes all relevant interdependencies and allocates the relevant data.

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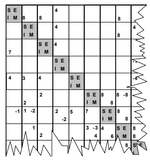
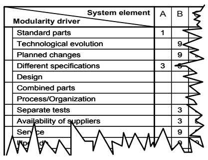
Method and Tools for Product Structuring

To support the product structuring we use:

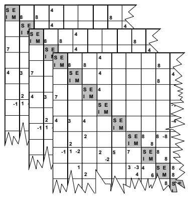
Design Structure Matrix



Module Indication Matrix



Reconfiguration Structure Matrix



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Phase Model

1 Analysis of the Development Task → **1** Objectives and constraints of product structuring

2 Analysis of the Product Concept → **2** Information about the product concerning the application of DSM, RSM and MIM

3 Product Structuring – Development of Extreme Views → **3** Extreme views of the product structure (Basis: DSM and RSM)

4 Product Structuring – Detailing and Integration of Further Information → **4** Finale product structure (Basis: DSM, RSM and MIM)

5 Evaluation → **5** Evaluated product structure

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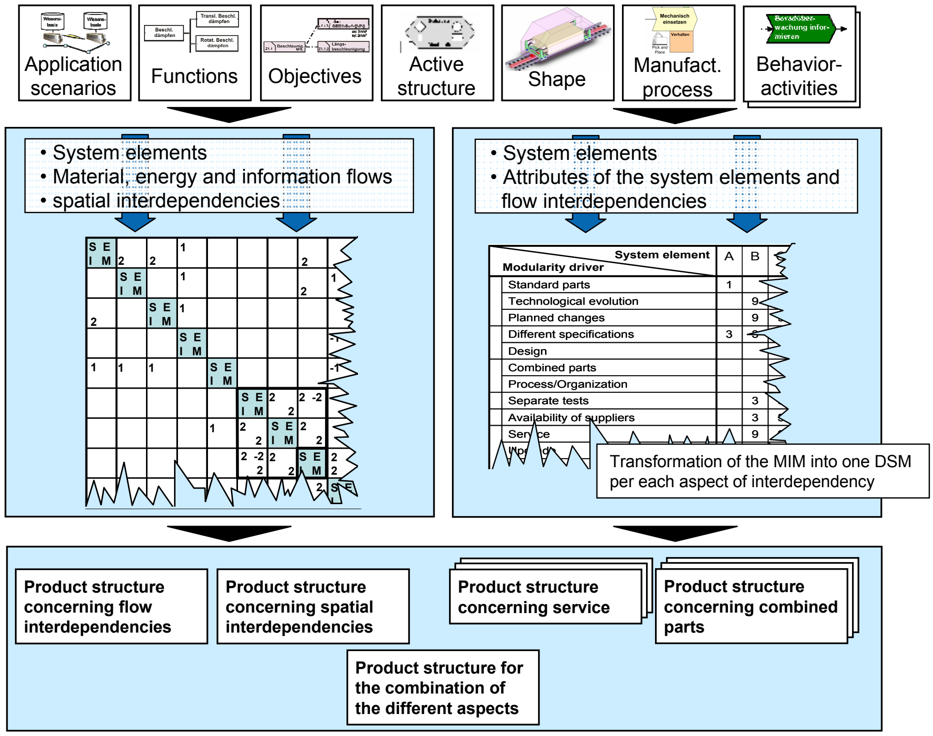
Application DSM and MIM



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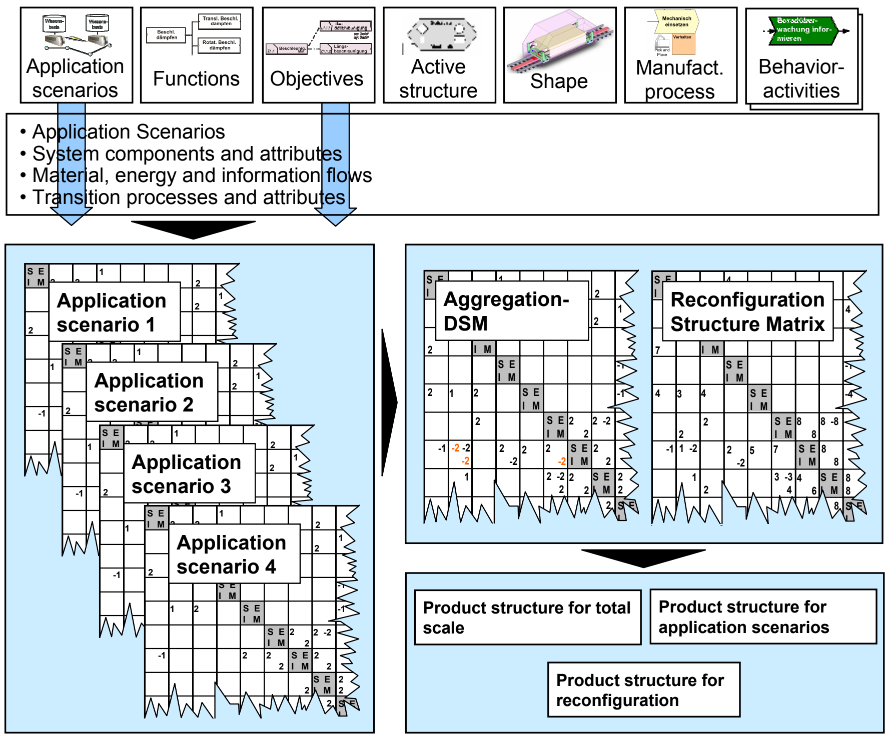
Application of RSM



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RailCab: An innovative Railway System for tomorrows Mobility

Demand and not schedule driven autonomous vehicles (shuttles) for passengers and cargo.

State of the art technology: Magnetic linear drive, mechatronics, communication technology. Standardized vehicles can be individually customized.

Passenger shuttle

Cargo shuttle

Convoy formation

Comfort version

Urban traffic version

Use of existing routes

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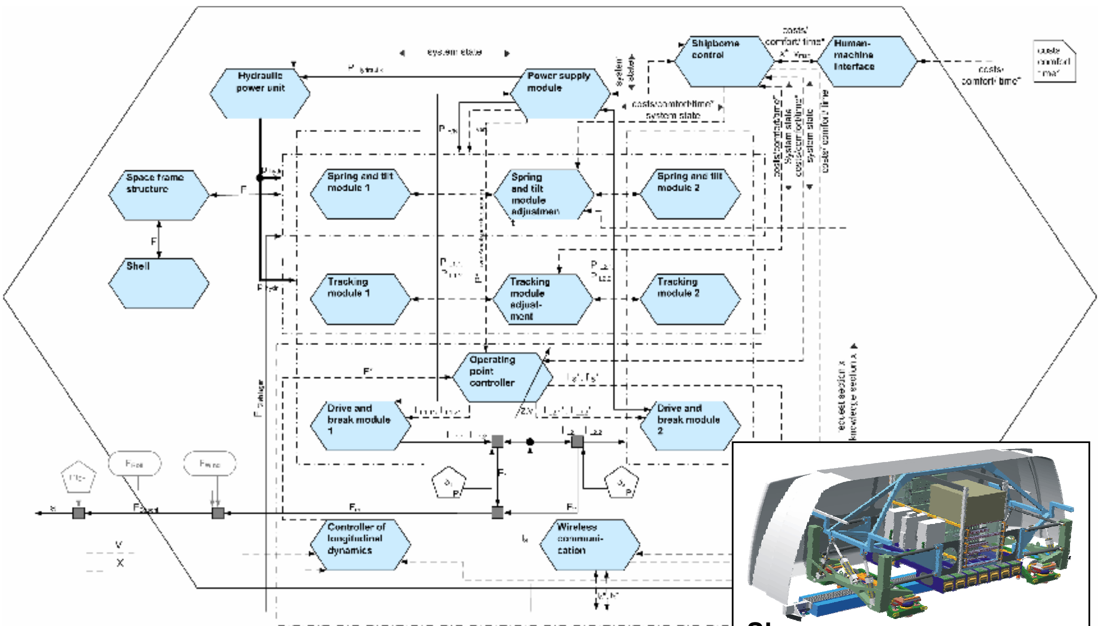
Example – RailCab NBP



Shape

Active structure

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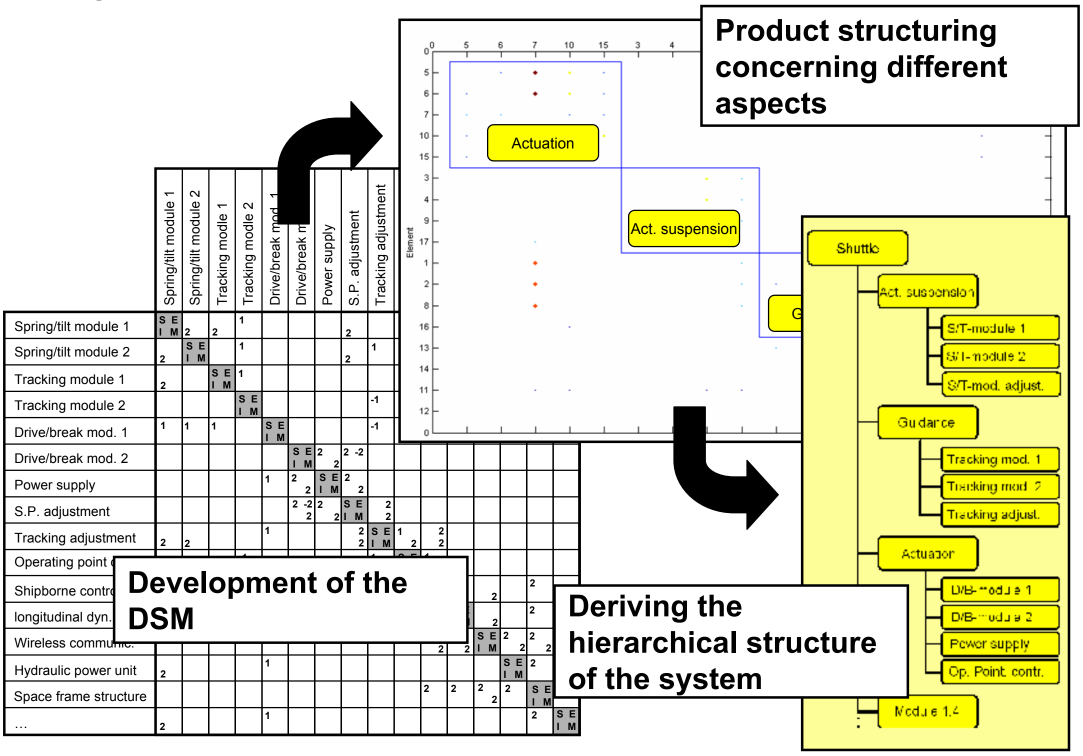
Example – RailCab NBP



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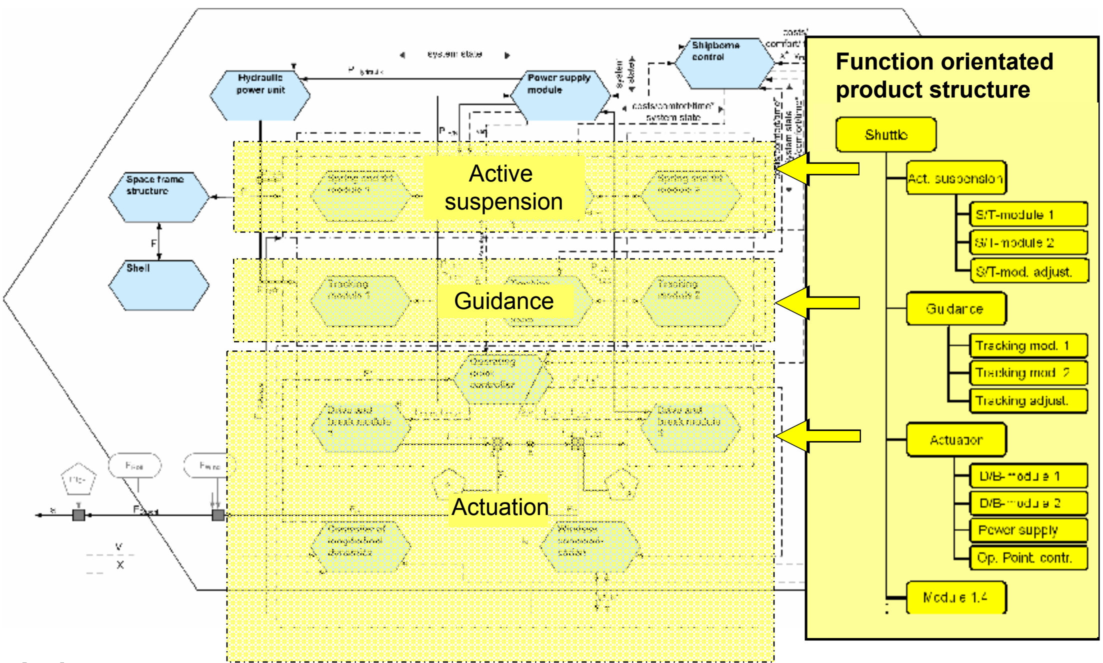
Example – RailCab NBP



Active structure

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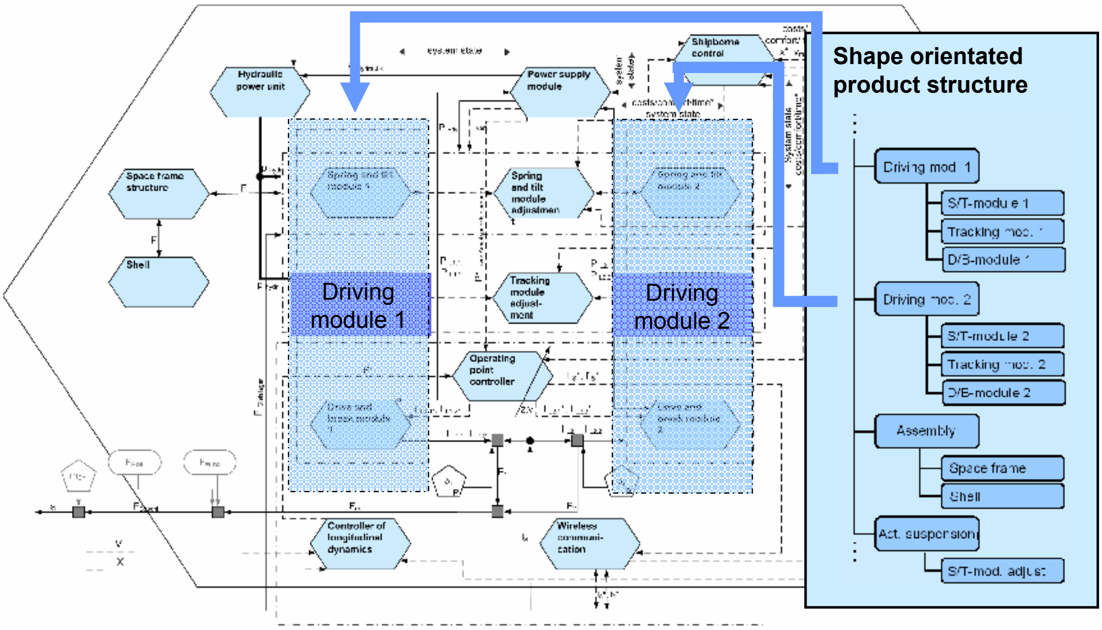
Example – RailCab NBP



Active structure

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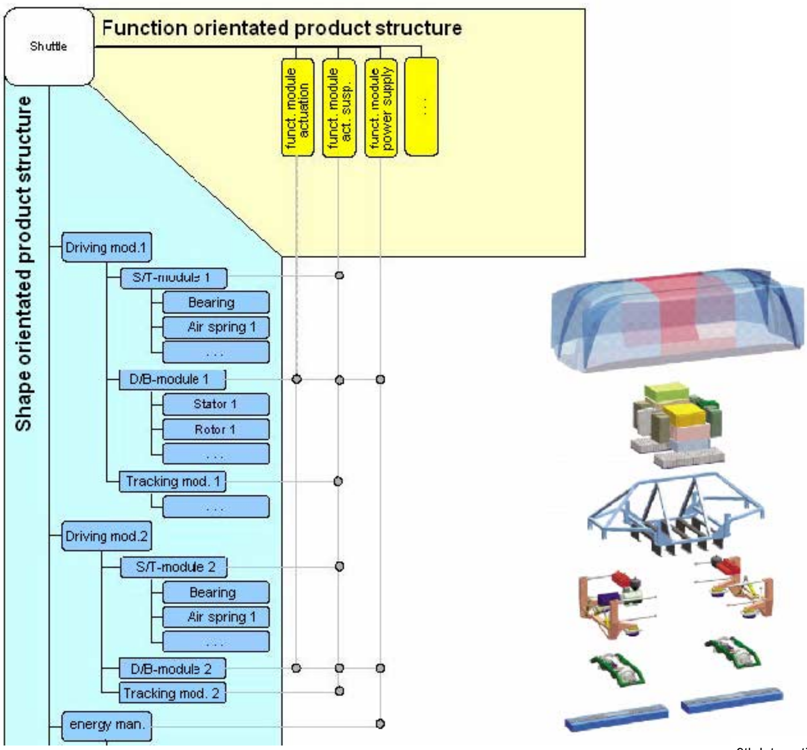
Example – RailCab NBP



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Conclusion

The presented method for modularisation…

… is generally applicable to a broad spectrum of different development tasks for mechatronic systems

… offers concrete design rules

… is supported by numerous established methods

… is integrated in the development process