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Understanding the Variation of Physical Elements and their Impact on Properties and Functions: A Case Study on Roll Stabilization Systems

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ABSTRACT

This paper explores the variation in physical elements, functions, and properties of roll stabilization systems in automobiles over successive generations. Two key methodologies, Characteristics-Properties Modelling (CPM) / Property-Driven Development/Design (PDD) and the C&C²-Approach (Contact and Channel Approach), are utilized to analyze the attributes of the system elements and their functional correlations. Through detailed comparison of traditional roll stabilization subsystems and the active roll stabilization system, the research uncovers several correlations between variation types and system properties. The findings show the importance of attribute variation for understanding complex mechatronic systems. The research results may guide future planning of new product generations and foster innovative solutions in the early phases of product development.

1. MOTIVATION

Schaeffler and Continental have developed an electromechanical roll stabilizer. This mechatronic, active roll stabilization innovation in automotive product development resolves the long-standing conflict between vehicle dynamics properties, such as lateral dynamics, and ride comfort at the complete vehicle level [1]. The principle of a “passive” roll stabilization whereby a stabilizer compensates the suspension differences during a cornering maneuver by a torsional movement is initially carried over to the mechatronic, active roll stabilization. In addition, however, new principles such as mechatronic amplification of the torsional moment and decoupling of the acting forces during road-induced suspension movements are integrated to improve both driving dynamics and ride comfort of a vehicle. In the complete vehicle, active roll stabilization enables higher maximum cornering speeds due to increased tire contact areas induced by a reduced rolling motion, while at the same time improving the property of driving comfort (especially in the case of road-induced excitations). Planning such innovations in new product generations at an early stage and understanding their development requires a comprehensive analysis of the principles, effects in the complete system and fulfilment of benefits. Accordingly, a core task of development is transferring the desired behavior of a product, described by means of target properties, into technical solutions. The success factor of a holistic understanding of the system and the consideration of all stakeholders is critical to the success of a product development process.

2. STATE OF THE ART

2.1 Model of PGE – Product Generation Engineering

The Model of PGE – Product Generation Engineering according to ALBERS [2] establishes product development strategies based on the deliberate incorporation of reference system elements (RSE) to form the basis for new products. Starting from the reference system [3], these RSE can be systematically integrated into a novel development project using the triad of principle, attribute, and carry-over variation methods [4]. The practical application of this model reveals that companies typically aim to develop a new product generation with as low a development share as possible, while ensuring enough novelty to maintain market appeal and competitive edge [5]. This approach is deemed economical and risk-averse. However, an essential part of innovation management involves balancing this strategy with a thorough market-environment analysis, to mitigate unanticipated competitor threats (both horizontal and vertical). ALBERS ET AL. [6] propose a general reference product model (see Figure 1), that categorizes technical products into properties, functions, and physical elements, across various system levels (supersystem(s), entire system, subsystem(s)).

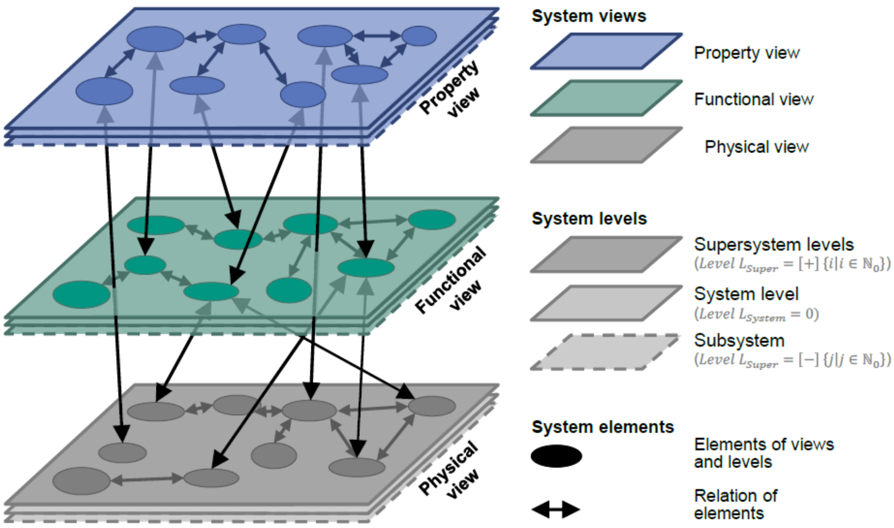


Figure 1: Basic reference product model in the model of PGE by Albers et al. [6, p. 360]

2.2 Properties, Functions and Physical Elements of Technical Systems

The development of technical systems requires a property-based requirements definition to consider key stakeholders, particularly customers and users [7]. Properties, defined as assessable design elements, allow developers to focus on user needs [8,9]. EHRLENSPIEL AND MEERKAMM [5, p. 30] further explain that properties enable the description of a system's behavior from various perspectives.

Functions, as defined by FELDHUSEN AND GROTE [10] and EHRLENSPIEL [11], represent the relationship between a system's input and output with the aim of accomplishing a task. The functional view of a system, therefore, outlines the system's desired behavior without considering the interacting physical solution elements [7,12].

The physical view of a system focuses on the tangible and intangible components of a data processing or mechatronic system [13,14]. This perspective is used to specify the technical solution, determining "How" the desired behavior and purpose of the system should be realized.

2.2.1 Characteristics-Properties Modelling (CPM) and Property-Driven-Development (PDD)

The CPM approach by WEBER AND WERNER [15] establishes a systematic relationship between the characteristics (C_i) and properties (P_j) of a system. It involves two key operations: analysis (R_j) and synthesis (R_j^{-1}). During analysis, the product's resulting properties are determined or predicted based on existing characteristics, which can be done physically or virtually. In contrast, synthesis involves determining the required characteristics, or combinations thereof, based on target properties. WEBER AND WERNER [15] consider this process as the core of product development, as it specifies the characteristics of solutions based on customer and market requirements (Figure 2) [16].

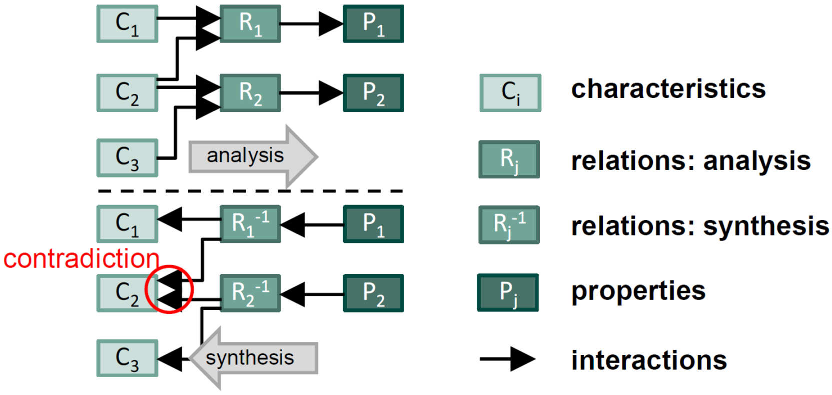


Figure 2: Analysis and synthesis and emerging conflict of objectives in WEBER's CPM approach [16]

Furthermore, the CPM approach can be extended to include characteristic-property relations by considering external conditions (EC_j). According to WEBER [16], these relations can only be meaningfully evaluated within the context of specific external conditions. For instance, different observers may perceive the relations differently during analysis, and factors like temperature can influence analysis results. Consequently, a realized technical system adheres to certain properties while considering external conditions (EC_j) [16].

Due to the complexity of synthesizing and analyzing properties and characteristics in the development process, computational assistance is necessary. Nonetheless, the procedures can be summarized in a simplified process model called Property-Driven Development (PDD) (Figure 3). PDD represents the process as a sequence of synthesis, analysis, and evaluation steps, aiming to achieve the defined target properties through the analysis-synthesis sequence. The goal during evaluation is to minimize the deviation between target and actual properties. The control loop is iterated as necessary, with further characteristics defined or varied for each run, leading to a more precise understanding of the system's behavior through the analysis of these characteristics [17].

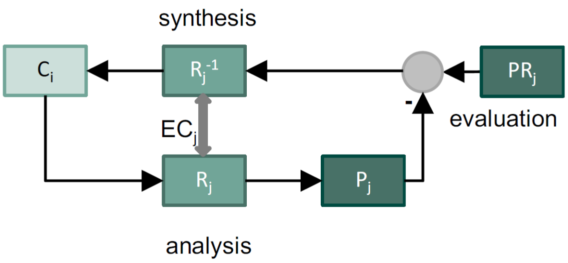


Figure 3: Process model: PDD – Property-Driven Development by WEBER [17]

2.2.2 Contact & Channel Approach (C&C² approach)

The Contact, Channel and Connector Approach (C&C²-A) developed by ALBERS AND MATTHIESEN [17] is a meta-model that has been applied for 20 years to facilitate the modeling of embodiment-function relationships (EFR) in product development [18]. This approach emphasizes the importance of considering the interplay between functionally relevant system components and the system environment [19]. ALBERS [20] highlights the need to describe objects generated during the development process in relation to their intended functions, ensuring transparency in achieving objectives. The C&C² approach aims to assist product developers in identifying parameters relevant to functions and promoting a systems thinking approach [21]. According to ALBERS AND MATTHIESEN [17], the core elements of the C&C²

model include working surface pairs (WSP), channel and support structures (CSS), and connectors (C):

- **Working surface pairs (WSP)** are surface elements that emerge from the contact between two arbitrarily shaped surfaces of solids or interfaces of liquids, gases, or fields. They facilitate the exchange of material, energy, and/or information [22].
- **Channel and support structures (CSS)** are volume elements that connect precisely two WSPs, allowing the conduction of substances, energy, and/or information between them [22].
- **Connectors (C)** are representative surface elements linked to a model of the relevant system environment, integrating properties beyond the current design domain into the system description [22].

The C&C² approach is based on three fundamental hypotheses that serve as the guiding principles for model building. These hypotheses emphasize the need for interaction (basic hypothesis 1) and minimum elements (basic hypothesis 2) to define a function. Additionally, the C&C² model building exhibits a fractal character (basic hypothesis 3) [17].

2.2.3 Roll Stabilization System in Vehicle Development

The stabilization system plays a crucial role in determining the driving characteristics of a vehicle, alongside the suspension and damper system. Typically, roll stabilization is achieved by utilizing elastic torsion bars that connect the wheel carrier to the axle, effectively limiting the lateral inclination of the vehicle during cornering. During the product development and tuning phase of a vehicle, the hardness of the stabilizer bar at the front and rear axles can be adjusted to influence the wheel load distribution and, consequently, the self-steering behavior during dynamic cornering. On the other hand, when encountering uneven road surfaces, such as bumps on one side of the road, the stabilizer system directly affects the suspension behavior by transmitting forces to the opposite side. Consequently, the design of the elastic torsion bars aims to strike a balance between minimizing lateral tilt for enhanced driving dynamics and ensuring high-quality suspension behavior for improved ride comfort. To address this trade-off, active roll stabilization systems have been developed, which utilize actuators to generate active forces on the stabilizers. These systems can effectively mitigate lateral tilt and actively influence the self-steering behavior, depending on the chosen technical solution principle. The evolution of the roll stabilization system across multiple generations has made it highly suitable for analyzing the variations in physical elements and their impact on properties and functions [23].

3. RESEARCH PROBLEM AND GOAL

In practice, products are not created on the “white sheet of paper” but are rather developed through the targeted variation of physical elements (especially hardware) over generations. This perception is explained by the model of PGE – Product Generation Engineering [2]. The mechatronic, active roll stabilization of a vehicle is an innovative successor generation of the “passive” roll stabilization, which itself can be described based on the variation types of PGE (carry-over, embodiment and principle variation). Since there is a correlation between the variation of properties, functions and physical elements, the product developer is able to describe a product generation in the Early Phase in the model of PGE both in a solution-open and solution-specific manner, including their interactions. By comparing the system of objectives (positioning objectives, requirements, boundary conditions, etc.) with the

architecture, conflicts and gaps between objectives can be identified at an early stage, which can be solved by new, "counter-intuitive ideas" – the Early Phase provides the time frame for incorporating such ideas into new vehicle generations. Practical research provides approaches such as "Characteristics-Properties Modelling" (CPM) / "Property-Driven Development/Design" (PDD) according to WEBER [3] or the Contact and Channel Approach (C&C²-A) according to ALBERS [4], enabling characteristics and properties to be planned or function-embodiment correlations to be analyzed. The consistent combination of the two approaches across different levels of a complex mechatronic system across product generations is still to be achieved.
The research project aims to systematically compare the classic subsystems of roll stabilization (stabilizer/ torsion spring) over generations with mechatronic, active roll stabilization to analyze and determine their differences in functionality and properties at different system levels (component to influence on the complete vehicle) (Figure 1). This should strengthen the understanding of the variation of attributes among different system elements and synthesize the understanding of properties and functions in the model of PGE. This leads to following research questions:

- How can the variation types of PGE (carry-over, embodiment, and principle variation) be used to describe the transition from passive to active roll stabilization?
- How does the correlation between the variation of properties, functions, and physical elements assist a product developer in describing a product generation in the Early Phase in the model of PGE?

4. RESULTS

4.1 Analysis of the variation of physical elements and their effects on properties and functions

4.1.1 Reference System Elements (RSE) of the Roll Stabilization System

In the initial stage, an analysis was conducted on the existing physical solution options for the roll stabilization system in currently available vehicles on the market. Three main variants were identified and chosen as the alternative Reference System Elements (RSE) for the roll stabilization system in this study (Figure 5). The original variant, known as the mechanical passive roll stabilization (PRS), is utilized in certain Porsche models such as the 718, 911, Macan, and Cayenne. It employs an elastic torsion bar spring connected to the wheel carriers via sway bars, allowing for passive control of the vehicle's roll during cornering. However, this RSE exhibits roll copying when subjected to one-sided road excitations, resulting in a moment in the same direction due to compression of the suspension springs (Figure 5, left).

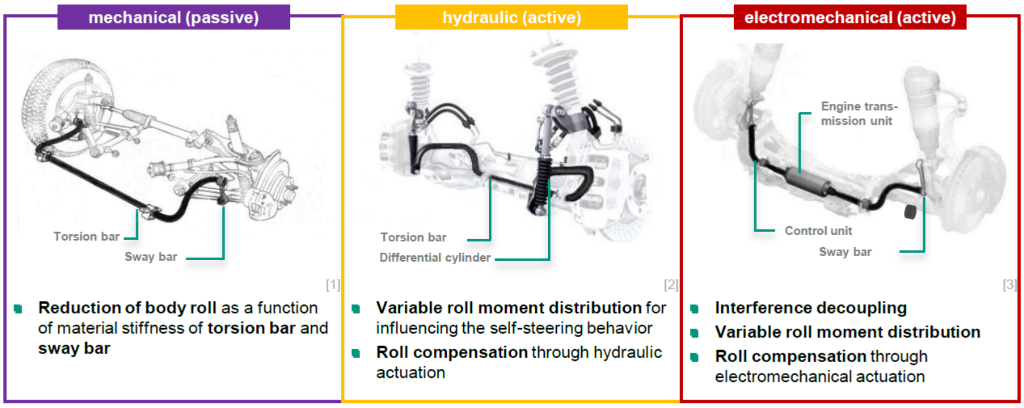


Figure 4: Overview of the alternative reference system elements (RSE) considered for passive, hydraulical active and electromechanical active roll stabilization [30]

In comparison to the PRS, the hydraulic active roll stabilization system (hARS) replaces the sway bar in the Porsche 911 with actively adjustable differential cylinders (see Figure 5, center). These cylinders connect the wheel carriers with the torsion bar spring, enabling electronically controlled pressure regulation of the hydraulic oil to influence the preload of the torsion bar spring. Through individual control of the hydraulic actuators based on driving conditions, the self-steering behavior can be positively affected. Additionally, the hARS provides active reduction of road-induced roll tendency and enhances vehicle stability by providing extra roll damping.

The third alternative solution, known as electromechanical active roll stabilization (eARS), is employed in the Porsche Taycan (Figure 5, right). It features an electromechanical actuator, consisting of a brushless DC motor and a three-stage planetary gear, positioned between the two halves of the torsion bar spring. Similar to the PRS, the torsion bar spring halves are connected to the wheel carriers via a pendulum support. The electromechanical actuation and control of the roll stabilization system allow for nearly complete active compensation of roll tendency due to its high actuation dynamics (approximately 30% faster reaction time compared to hARS). In addition to mitigating roll copying, the eARS can effectively absorb or decouple disturbances affecting roll damping. Another advantage is the eARS's ability to deliver full power consistently, whereas the hydraulic pump of the hARS is typically driven by the vehicle's internal combustion engine, resulting in limitations at low engine speeds. The eARS offers greater flexibility in terms of system integration, reduced maintenance requirements, potentially lower system costs compared to hydraulic systems, and promotes energy efficiency due to its power-on-demand principle.

4.1.2 Definition of the Relevant Use Cases and States

The dynamic use cases where the roll stabilization system significantly impacts vehicle behavior were analyzed. Among the four extreme cases, we examined the static states of the system based on context. The primary focus was on two of the four relevant use cases for the roll stabilization system: driver-induced roll motion (via connector user C_A) and road-induced roll motion (via connector road C_F).

An example of **driver-induced roll motion** is swerving during evasive maneuvers or sudden cornering (state 1.1). This action applies force to the vehicle's body as lateral acceleration, creating a rolling moment due to centrifugal force acting on the center of gravity. The load change reaction (state 1.2) isn't further considered due to its identical effect to the reversal of steering direction [24].
Road-induced rolling motion involves one-sided road unevenness like curb rise/impact hole exit (state 2.1) or road dip/impact hole entry (state 2.2), applying force to the wheel as normal force changes due to asymmetrical road unevenness [24].
The control of active roll stabilization systems in today's vehicles can often be adjusted via the **driving program** (via Connector user C_A) [24]. In "Sport" mode, the emphasis is on dynamic driving characteristics, while "Comfort" mode prioritizes driving comfort. As comparison with passive roll stabilization isn't possible, Use Case 3 is disregarded.
Environmental or aerodynamic forces, such as wind when crossing a bridge, can induce vehicle roll. The lateral vehicle base area greatly influences this. However, due to the lack of a consistent product variant for all three roll stabilization systems, Use Case 4 is also dismissed.

4.1.3 Determination of the Logical and Physical System Architecture

Product developers have the responsibility of selecting or modifying the logical reference system elements (RSE) at various system levels, or reconfiguring a new product to fit within these levels. This process aligns with the concept of a G_1 in the PGE model (ALBERS ET ALL. [25]). It is important to note that a product can also serve as a subsystem of another product within the same domain [26]. For instance, the transmission is both a product from an automotive supplier and a subsystem within a vehicle produced by an Original Equipment Manufacturer (OEM) in the automotive industry [26]. From the perspective of the automotive OEM, the vehicle represents a monolithic system comprised of subsystems, forming a context-dependent system within the associated supersystem (ALBERS ET ALL. [30]). However, when considering vehicles, smartphone apps, and transportation infrastructures collectively, they can be viewed as a supersystem working seamlessly together to meet customer and user needs. This integration of individual autonomous systems results in a System of Systems (SoS) that enables seamless mobility [27]. Thus, in this example, the outlined supersystem level can be characterized as an SoS. Depending on the observer (e.g., domain, organization, or product developer), the hierarchical structure may differ, encompassing system levels and super- and subsystem levels. Standardizing a global view within a domain, industry, or value chain can be advantageous. An example of this is the labeling system for rail vehicles (DIN DEUTSCHES INSTITUT FÜR NORMUNG E.V. [28]), which adopts a consistent hierarchization of system levels within the domain (Figure 5, left). The benefits of this standardization include more efficient subcontracting of subsystem development, standardized tests/validation, and releases specific to the domain. However, within organizational structures, a differentiated view can be adopted.

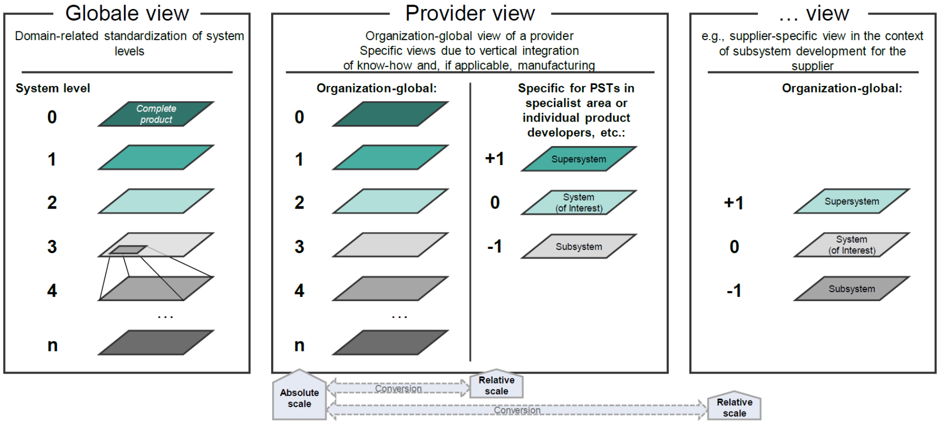


Figure 5: System levels in the model of PGE [30]

In this case, a hierarchy of system levels can be defined globally within the organization or specific to a provider. Problem-solving teams within the supplier's specialist departments or individual product developers can define their own "system of interest" level and, for example, convert an absolute scale relative to it (Figure 5, center). Similarly, a supplier developing a subsystem for a provider or another provider contributing to a supersystem can align with the defined system levels using a relative scale (Figure 5, right). To ensure comparability of observations and analysis results, a logical system architecture was defined for the vehicle system in the study. This architecture was derived from observations in the automotive industry and aims to describe systems without imposing specific technical solutions, serving as a "reference system architecture" across multiple generations.

The vehicle system is part of a supersystem, which can be described as a mobility system, for example. When combined with the infrastructure, it forms a System-of-Systems (SoS) (e.g., ALBERS ET ALL. [30]). Within the defined logical system architecture, the vehicle system is initially divided into four systems at level 2: driving system, body system, energy system, and communication system (Figure 6). The roll stabilization system, the focus of this study, is depicted at level 3 as a subsystem of the driving system. Additional level 3 subsystems connected to the stabilization system through interfaces and interactions are also included.

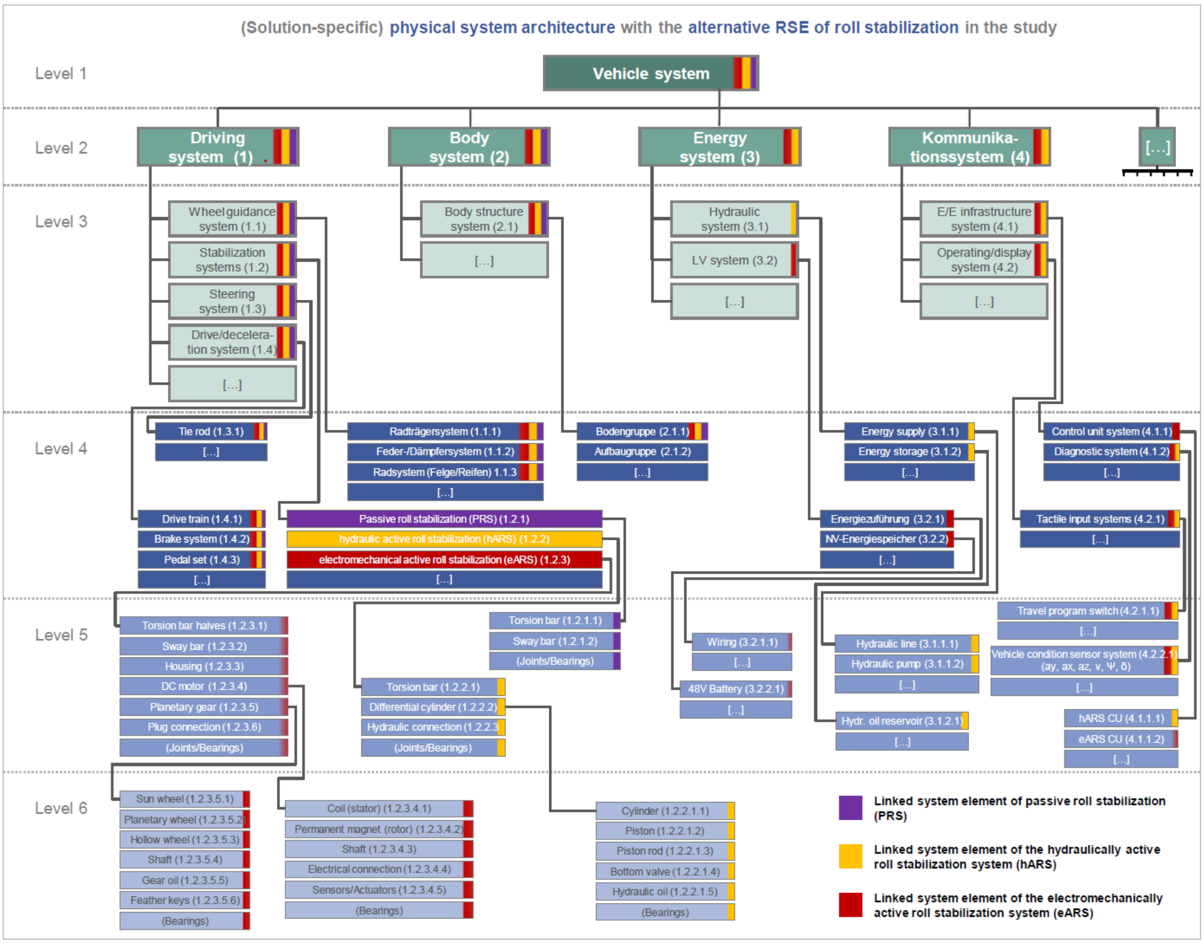


Figure 6: (Solution-specific) Physical system architecture for levels 4,5 and 6 *[30]*

Based on the defined logical system architecture, a physical system architecture specific to the solution was developed. This architecture consists of three further subsystem levels, which help identify the three alternative RSEs of the roll stabilization system and their constituent subsystems, which are the main focus of this study (cf. Figure 6). The system elements are assigned to the three alternative RSEs: PRS, hARS, and eARS. These elements are color-coded in Figure 8 to indicate their association with the respective RSEs. In practice, only one alternative solution of the roll stabilization system can be implemented in a vehicle at a time. While theoretically different variants could be used for the front and rear axles, it is practically challenging due to the associated costs, complexity, and effort. Consequently, only the color-coded variants are presented. Thus, only the system elements linked by color coding are necessary, while the others are considered superfluous from the perspective of a specific roll stabilization variant. In this study, the roll stabilization of the steered front axle is addressed in a simplified manner. To provide clarity, the effects of the physical elements of the three alternative roll stabilization systems are also indicated in the logical system architecture.

4.1.4 *Effect Diagrams in System Levels 1,2, and 3*

To illustrate the relationships between use cases in the logical system structure, effect diagrams were created for levels 1, 2, and 3.

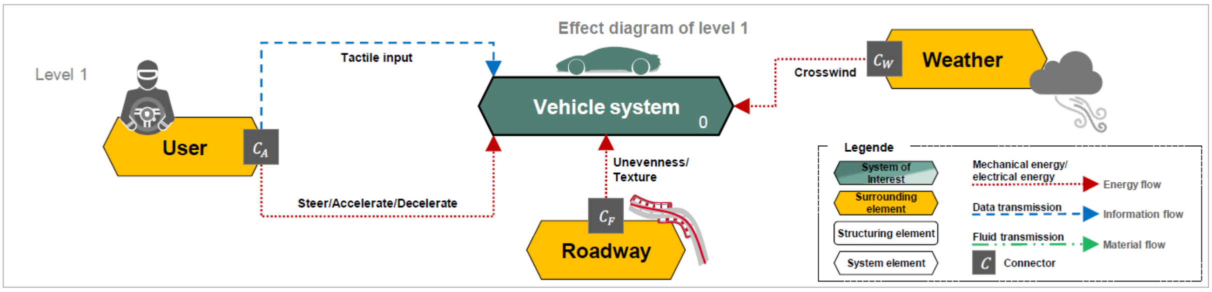


Figure 7: Level 1: Vehicle System [30]

At level 1, the vehicle system is influenced by three environmental elements: the user, road surface, and weather (Figure 7). Crosswind affects the vehicle system through the C_W connector (use case 4), while road surface conditions affect it through the C_F connector (use case 1). The user can influence the vehicle system through steering, acceleration, and deceleration (energy flow in Use-Case 2), as well as through tactile inputs via the C_A connector (data transmission in Use-Case 3 – only possible with hARS/eARS)

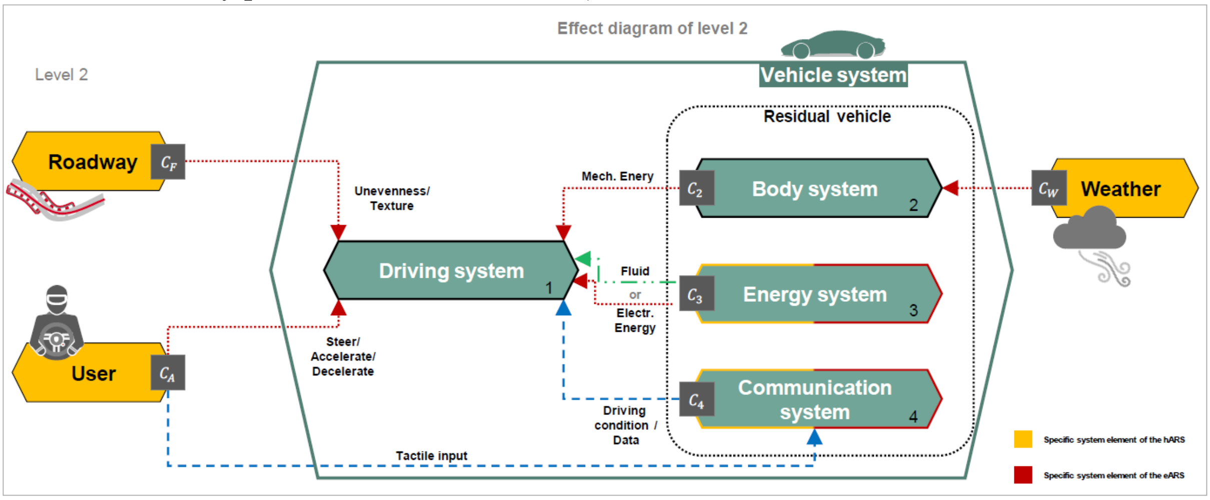


Figure 8: Level 2: Driving System [30]

At level 2 (Figure 8), it becomes clear that weather directly affects the body system via C_W and the road affects the driving system via C_F. The user influences the driving system through C_A with driving commands and tactile inputs, depending on whether hARS or eARS is used. Mechanical energy flows from the body system (via C_2), and fluid (hARS) or electrical energy (eARS) flows from the energy system (via C_3) to the driving system. The communication system sends information to the driving system through C_4, including driving status or selected driving program (only for hARS/eARS)

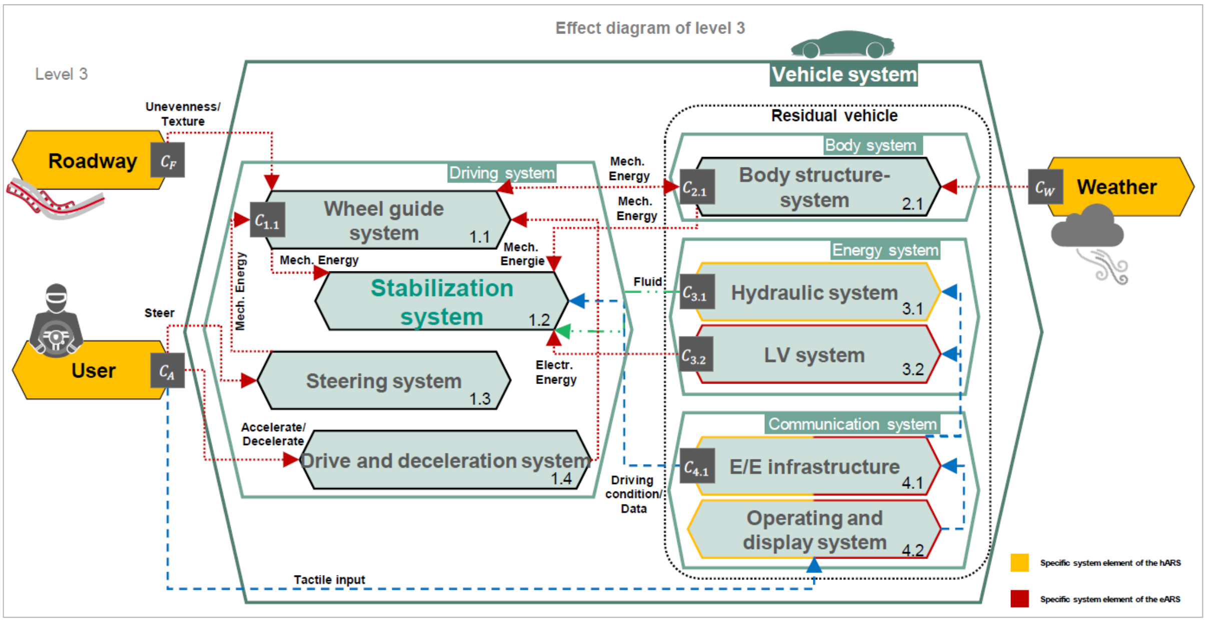


Figure 9: Level 3: Stabilization System [30]

The detailed effect diagram of level 3 (Figure 9) reveals that the roadway directly and unrestrictedly affects the wheel guidance system in the driving system. User energy input is divided between the steering system and the drive and deceleration system, both of which transfer mechanical energy to the wheel guidance system. Weather conditions experienced by the body structure system are transmitted to the wheel guidance system and the stabilization system through mechanical energy. In the case of hARS, the stabilization system is supplied with hydraulic fluid from the hydraulic system, while eARS receives electrical energy from the low-voltage system. Tactile inputs from the user, such as driving program selection, are processed by the control and display system, forwarded to the electrical/electronic architecture, and then sent to the stabilization system

4.1.5 C&C² Models, Functions, and Properties for RSE Analysis

The C&C² approach was used to analyze the three alternative RSEs (roll stabilization systems) at level 4. This approach links functions with working surface pairs (WSP) and channel and support structures (CSS) [29]. The study determined the WSP and CSS for the passive and two active roll stabilization systems (Figure 10 and Figure 11).
The function structure demonstrates the variation across RSE variants by identifying functionally relevant effect locations, principles, and movements (Figure 12). Property structures illustrate the effects on the overall system and subsystem levels (Figure 13). The analysis involved capturing system interfaces and interactions with other subsystems on level 4. Connectors were used to trace information inheritance and specify the influence of the RSEs. The connectors include couplings, joints, and connections to the energy supply and communication systems. The C&C² analysis of the **mechanical Passive Roll Stabilization (PRS)** revealed the WSP between the torsion bar spring and sway bars. The PRS's main function is to passively reduce driver-induced roll, achieved through torsional movement and force transmission (Figure 10).

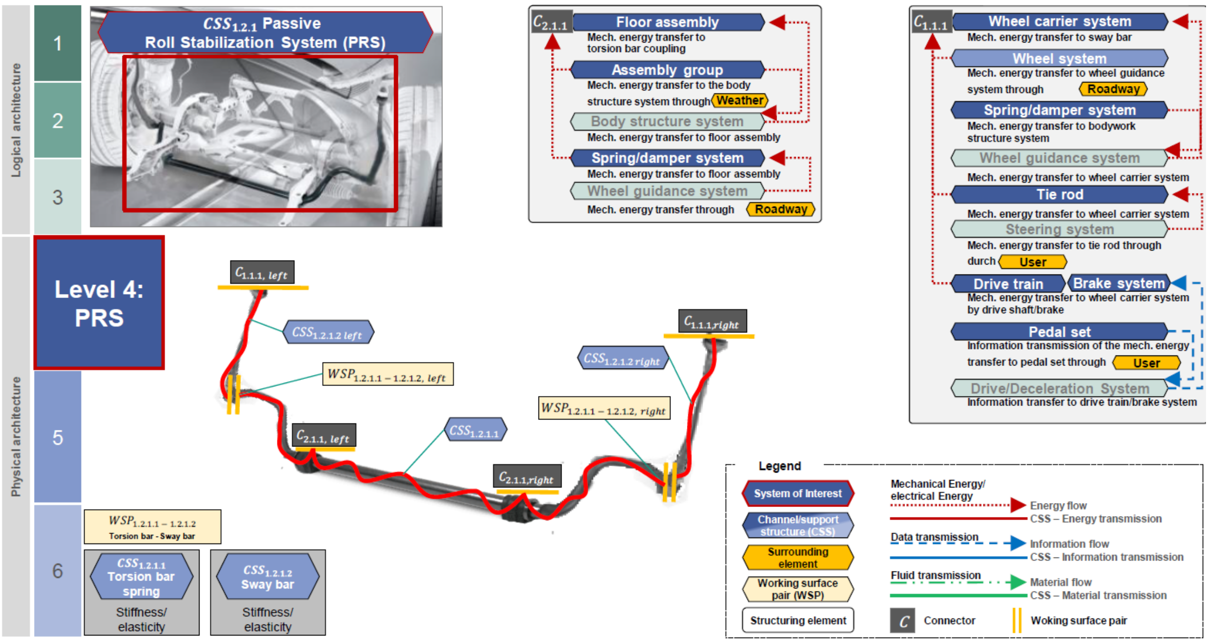


Figure 10: C&C² model on level 4: Passive Roll Stabilization (PRS) [30]

The C&C² analysis of the **hydraulical Active Roll Stabilization** (hARS) (Figure 11) showed how it actively reduces driver-induced and road-induced roll. By controlling hydraulic pressure, the differential cylinders counteract wheel carrier movement and support roll damping . In the hARS, the sway bars of the PRS are replaced by differential cylinders ($CSS_{1.2.2.2}$) and supplemented with a hydraulic connection ($CSS_{1.2.2.3}$). The torsion bar spring ($WSP_{1.2.2.1}$)) remains unchanged. There is one WSP between the torsion bar spring and each differential cylinder ($WSP_{1.2.2.1-1.2.2}$). Connectors $C_{2.1.1}$ connect the torsion bar to the floor assembly, while connectors $C_{1.1.1}$ link the differential cylinders to the wheel carriers. An additional WSP ($WSP_{1.2.2.2-1.2.2.3}$) exists between the differential cylinder and the hydraulic connection. Connector $C_{3.1.1}$ connects to the energy supply system for fluid transfer.

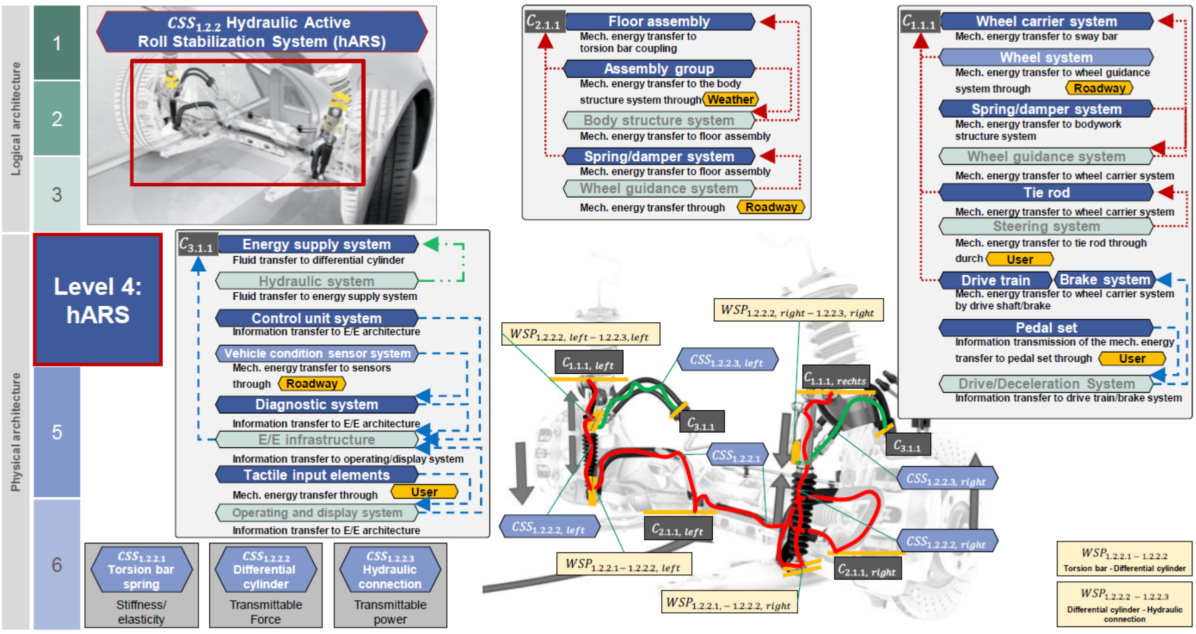


Figure 11: C&C² model on level 4: Hydraulic Active Roll Stabilization (hARS) [30]

The hARS varies the basic functionality of the PRS, allowing active reduction of vehicle roll in response to steering inputs. Hydraulic pressure control ($C_{3.1.1}$) enables length changes in the differential cylinder ($CSS_{1.6.3.4}$) via $WSP_{1.2.2.1-1.2.2.2}$, counteracting wheel carrier movement. Sensor-equipped vehicles can actively reduce driver-induced roll through information processing. The hARS also reduces road-induced roll, softening the sway bar ($WSP_{1.2.2.2-1.2.2.3}$) to support roll damping. This achieves improved driving dynamics and comfort.

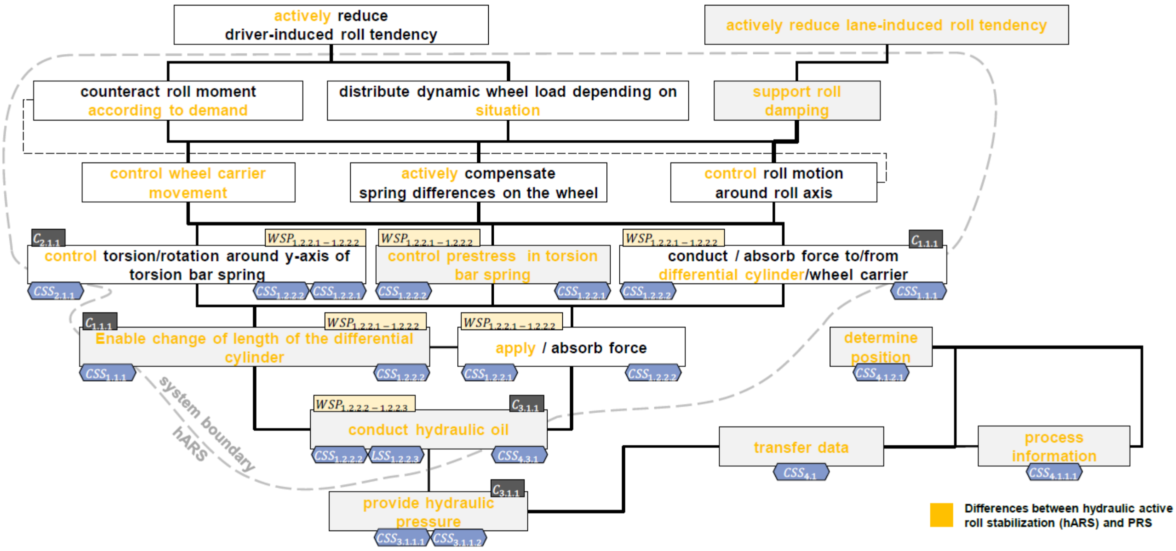


Figure 12: Comparison of the function structure of the hARS and PRS [30]

The hARS offers control over characteristics such as geometric dimensions and viscosity, influencing properties like transmissible power and forces in the differential cylinder. At the vehicle level, it enables situation-dependent roll angle control for driver-induced roll and reduces roll copying for road-induced roll. This enhances driving dynamics and comfort simultaneously.

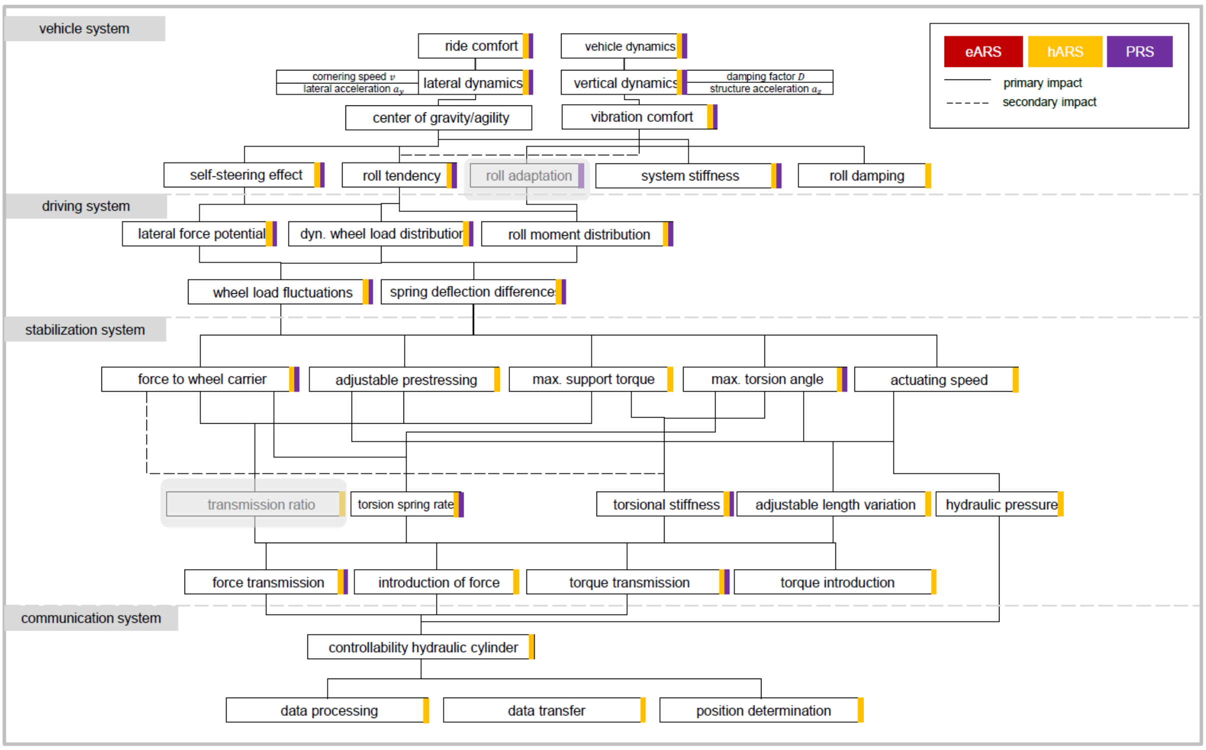
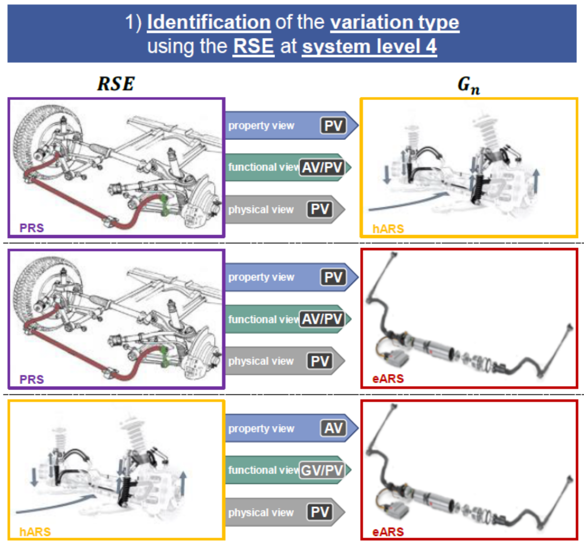


Figure 13: Comparison of the property structure of the hARS and PRS [30]

The C&C² analysis of the **electromechanical Active Roll Stabilization (eARS)** revealed its ability to actively reduce driver-induced and compensate for road-induced roll. The torsion bar halves can be decoupled to allow one-sided deflection, improving ride comfort. The eARS outperforms the hARS due to its control dynamics and full compensation of roll tendency.

4.1.6 Variation of RSE on the perspective of function, property, and physical parts

Based on the C&C² analysis at system levels 4 and 5, the study examined the phenomena of variation in the roll stabilization system (RSE) from both function and property perspectives (Figure 14).



2) Calculation of the variation shares using the constituent subsystems at system level 5

system view / variation type	physical view	functional view	property view
CV	33%	14%	29%
EV / AV / AV	0%	22%	29%
PV	67%	64%	42%

system view / variation type	physical view	functional view	property view
CV	17%	11%	14%
EV / AV / AV	27%	17%	29%
PV	66%	72%	57%

system view / variation type	physical view	functional view	property view
CV	0%	59%	10%
EV / AV / AV	14%	0%	38%
PV	86%	41%	52%

Figure 14: Variation Types and Shares of Constituting Subsystem Elements in the Roll Stabilization System [30]

For carry-over variation (CV), the mechanical passive roll stabilization system was assumed to be carried over into a new product generation, with no changes in functions observed. Embodiment variation (EV) involved partially varying the hydraulic active roll stabilization system while retaining the solution principle. No new functions were introduced, but changes in existing properties were triggered. Principle variation (PV) resulted in a new solution principle, introducing new main functions and additional subfunctions, as well as new properties and changes in attribute values.
The study compared observable variation types between the three RSE alternatives and calculated variation shares based on subsystems. Embodiment variation (EV) focused on physical elements, while a generic attribute variation (AV) was introduced to describe variation from function and property perspectives. The calculated variation shares showed different distributions among the variation types when considering the constituent subsystems from a physical viewpoint. Carry-over variation (CV) and principle variation (PV) constituted the majority of the variation shares.
In terms of main functions, attribute variations were observed in the first main function between different RSE alternatives, while the second main function represented principle variation in each case. Subfunctions showed varying shares of CV, AV, and PV. Comparing properties at system level 4, variations in attributes and new properties were identified. However, a detailed analysis of constituent subsystems and characteristics influenced by product developers was necessary to avoid misleading results.
The calculation of variation shares based on subsystems at system level 5 revealed the distribution of CV, AV, and PV in properties.

The findings demonstrate the complex interrelationships between the types of variation in different system elements and contribute to a better understanding of properties and functions in the roll stabilization system. These insights can be applied to further research and development, production systems, strategies, and business models.

5. DISCUSSION

The relationship between physical embodiment variation and the variation of functions and properties was studied, leading to the generalization of findings (Figure 12).

trigger		effect	
variation type (physical view)	description based on theC&C² approach	functions	properties
carry-over variation (CV)	▪ only adaptations to the connector(s) of the physical element possible ▪ quantity, layout and embodiment of the channel and support structure (CSS) and working surface pair(s) (WSP) remain unchanged	▪ due to the unchanged quantity and characteristics/embodiment of the CSS and WSP, the function also remains identical ▪ changes to the connector(s) trigger changes in the characteristics of functions at higher levels in the system under consideration	▪ CV of a physical element does not trigger a change of the properties in the system element under consideration ▪ changes to the connector(s) trigger changes in the attributes of properties at higher levels in the system under consideration
embodiment variation (EV)	▪ Number of CSS and WSP of the physical element remain unchanged ▪ layout and embodiment changes without removing or adding WSP	▪ due to the constant quantity of CSS and WSP, the EV of a physical element does not trigger any intended/desired changes in the expression of function or principally new functions in the system element	▪ due to changed characteristics (e.g. material, geometry) in the system element, the EV of a physical element triggers changes in the attributes of properties. ▪ however, a EV of a physical element does not trigger any new properties in principle
principle variation (PV)	▪ quantity of CSS and WSP is changed ▪ PV PV always implies EV ▪ new solution principle in the physical element	▪ due to the changed quantity of CSS and WSP, a PV of a physical element triggers in principle new functions in the system element ▪ in addition, identical, modified or principally new functions are possible at higher levels of the system under consideration	▪ PV of a physical element triggers new property in the considered system element ▪ PV of a physical element triggers changes in the attributes of properties at higher levels in the system under consideration

Figure 15: Generalization of the connection between C&C² models, functions and properties [30]

When there is a constant number and attributes of the physical embodiment of working surface pairs (WSP) and channel and support structures (CSS), variations in physical elements result in carry-over of identical functions in the roll stabilization system (RSE). Changes in physical element connectors only affect function attributes at higher system levels. Similarly, no new properties can be triggered within the considered system element through component variation (CV). Changes in higher-level properties are also consequences of connector changes. Embodiment variation involves changes in attributes and arrangement of WSP and CSS while maintaining the underlying solution principle. However, new WSP or CSS cannot be added or removed, preventing the realization of desired changes or new functions within the system element through embodiment variation (EV). EV does trigger changes in property attributes due to alterations in characteristics such as material and geometry. However, fundamentally new properties cannot be achieved through EV because the solution principle is carried over. On the other hand, principle variation of a physical element allows the realization of new functions through changes in the number of WSP and CSS. It also enables the realization of identical functions with different attributes or fundamentally new functions, as well as properties at higher levels of the overall system.

In the PGE model, the variation operator describes carry-over, embodiment, and principle variation of system elements in relation to physical embodiment (WSP & CSS). To describe variation in different types of system elements (e.g., functions, properties, construction kit components, strategy), a clear and intuitive generic description is needed. ALBERS ET AL. [4] introduced the concept of generic attribute variation (AV) in the PGE model, applicable to any system element type. The study highlights the strong interaction between different system views and element types. Therefore, the following section derives an understanding of properties and functions in the context of KaSPro - Karlsruhe School for Product Engineering and the PGE model.

6. OUTLOOK

In this case study, relationships between different system elements: properties, functions, and physical elements where identified. Variation in properties and functions, particularly embodiment variation (EV), cannot be directly transferred. Combining the CPM/PDD and C&C² approaches has led to the conclusion that the PGE model in system understanding requires the addition of attribute variation (AV). The CPM/PDD approach has enhanced the understanding of relationships between properties, characteristics, and their attributes in studied product generations. The combination of C&C² and CPM aids in planning characteristics, functions, and physical elements across generations, revealing patterns in how changeable characteristics impact properties at different system levels. Furthermore, it facilitates the identification and planning of solution-open and solution-specific elements based on knowledge of cause-effect relationships and customer experience. These findings contribute to a comprehensive understanding of properties and functions in product development, enabling their transfer to production systems, strategy, and business models.

7. NOTICE

This paper is based on the whitepaper "Analysis of the Variation of Physical Elements and their Effects on Properties and Functions using the Example of Different Generations of the System "Roll Stabilization" by Albert Albers, Tobias Hirschter, Joshua Fahl, Simon Rapp, Kevin Rehn, Steffen Haag (2022), intended for the Ilmenau Scientific Colloquium.

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