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Procedia CIRP 91 (2020) 781–788

www.elsevier.com/locate/procedia

30th CIRP Design 2020 (CIRP Design 2020)

Influencing factors on the retrospective analysis of variation shares with C&C²A-based criteria in Product Generation Engineering

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Abstract

New technical systems are created on the basis of existing systems by different extent of taken over and newly developed and/or adapted subsystems and their linkage. Various approaches aim to characterize these different forms of technical adaptation and to make them formally measurable. The calculation of variation shares according to the model of the PGE is based on the determination of variation types with the help of the C&C²-A modelling of subsystems and the associated reference system element as well as the subsystem structure. Both can generally be selected variably. This contribution investigates the influence of these two parameters on the retrospective analysis of variation shares, using a test bench probe and an actuator in a tooling machine as examples. Variation shares are calculated for different levels of detail of the underlying C&C²-A modelling and subsystem structures with different numbers of subsystems. Observed effects regarding the identification of the variation type of a subsystem as well as regarding the calculation of variation shares for the whole system are discussed. A major conclusion of the investigation is that retrospective analyses of variation shares depend strongly on the two investigated parameters and are mostly not unambiguous.

Keywords: product architecture; product architecture change; product development; variations of product architecture

1. Introduction

New technical systems are created on the basis of existing systems by different extent of taken over and newly developed and/or adapted subsystems and their linkage [1]. This creates innovation potential, but also challenges and development risks. Various approaches aim to characterise these different forms of technical adaptation in the broadest sense and to make them formally measurable as the basis for empirical studies. [2]. In the model of the PGE - Product Generation Engineering, this is described by different types of variation, which can be recorded by investigating the changes in the Wirk-Structure of systems. This paper examines the influencing factors "system structure" and "depth of detail of the modelling of the Embodiment-function-relation" in the formalised description of variations using the retrospective analysis of two case studies.

The calculation of variation shares according to the model of the PGE is based on the determination of variation types with the help of the C&C²-A modelling of subsystems and the associated reference system element as well as the subsystem structure. Both the subsystem structure and the depth of detail of the modelling with C&C²-A can generally be selected variably. Therefore, the following questions arise regarding the influence of these two factors on the calculation of variation shares:

- What influence do the selected subsystem structure and the selected level of detail of the C&C²-A modelling have on the retrospective determination of variation types of individual subsystems?
- How do the selected subsystem structure and the

10.1016/j.procir.2020.02.235

selected level of detail of the C&C²-A modelling affect the calculation of the variation components?

2. Literature review

The creation of new products, including new variants, on the basis of existing products by different forms of carryover or adaptation is described by different approaches, for example Design Reuse [3], Engineering Change [2] or the model of the PGE - Product Generation Engineering [1].

An engineering change can be anything from a small revision of a diagram to a major redesign operation [2]. Based on Terwiesch and Loch [4], Jarratt et al. [5] provide a more complete definition:

"An engineering change is an alteration made to parts, drawings or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time."

Henderson & Clark [7] distinguish between the extent to which subsystems or their networking are changed. The adaptation of the networking of subsystems is also understood as the adaptation of the product architecture. According to Ullrich [8], the product architecture is a scheme with which the function of the product is assigned to its physical components. A functional element is a certain function of a product and physical elements implement the functional elements of a product.

In practice, most products are somewhere between full modularity [9] and full integration. Whether a product is considered modular or integrated depends on the level at which it is examined. Products may consist of subsystems that are modularly interconnected, but each can be highly integrated [10].

The product architecture has influences on different areas [11]. In product development, a high modularity of the product allows a simpler derivation of new product variants. The parallel development of components through decoupling and interface standardization also reduces the development time [9]. Despite the many advantages offered by modular architectures, integral products can often be developed faster and still achieve the same function [10].

The model of PGE according to Albers [1] is used to describe fundamental observations during the development of new technical products. The PGE model can be described by two basic hypotheses.

Every product development is based on already existing subsystems or concepts from a reference system. This is defined as follows:

"The reference system for the development of a new product generation is a system whose elements originate from already existing or already planned socio-technical systems and the associated documentation and are the basis and starting point for the development of the new product generation." [6]

There are three types of variation that describe the development of the subsystems of a new product generation. An adjustment of subsystems is called a carryover variation (CV). A new development takes place through a embodiment variation (EV) or a so-called principle variation (PV) [1].

However, subsystem subdivision can be variable. Based on the model of the PGE, the variations can be characterized there by modelling the embodiment-function-relation using the Contact & Channel Approach (C&C²-A) [12] and analyzing changes in this context. C&C²-A models are created in order to explicitly map concrete embodiment-function relations. Model elements and rules (basic hypotheses) for their application in modelling are used for this purpose. With the three core elements Working Surface Pairs (WSP), Channel and Support Structures (CSS) and Connector (C) [13, 14] design and function are connected in the technical system [15].

Albers et al. investigated the variations using the example of the dual mass flywheel (DMS). In the context of the Contact & Channel Approach, the WSP and CSS remained mostly unchanged during a carryover variation. Variations occurred only in the WSP to the Connectors, which represent the adjacent subsystems [16]. The DMS housing in the fourth DMS generation investigated serves as an example, which, as can be seen in Figure 1, was taken over from the third DMS generation.

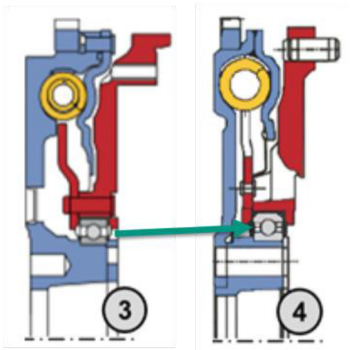

Figure 1 - DMS-Generation 3 and 4 with CV [16]

A characteristic feature of an EV is that the solution principle used is retained in the reference system, but the form is changed [16].

Figure 2 shows an Embodiment Variation using the DMS rolling bearing as an example. The outer diameter of the rolling bearing was significantly reduced during the transition from the fourth to the fifth generation. The bearing principle and the bearing solution of the deep groove ball bearing were not changed [16].

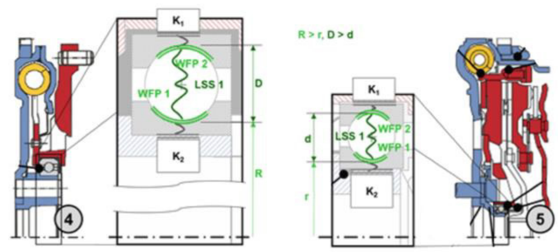

Figure 2 – EV using the DMS rolling bearing as an example [16] (figure adapted). Blue is the primary mass of the DMF, red the secondary mass, yellow are the coil springs between the two masses.

A PV is always accompanied by a change in the number of WSP and CSS. In the following example, the bearing principle was varied from a double row deep groove ball bearing to a single row deep groove ball bearing during the transition from the first to the second DMS generation (Figure 3) [16].

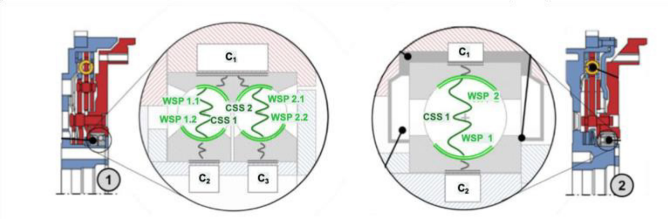

Figure 3 - PV: Change of the bearing principle in the second product generation of dual mass flywheels (DMF) as described in [16] (figure adapted). Blue is the primary mass of the DMF, red the secondary mass, yellow are the coil springs between the two masses.

Starting from the variation of subsystems, variation shares can be calculated for the entire system. The mathematical description model divides the number of all subsystems of a new product generation into three subsets according to the type of variation identified with regard to the development. Subsystems (SS) adapted by carryover variation (CV) are abbreviated as CS, ES are the subsystems newly developed by embodiment variation (EV) and the set of subsystems newly developed by principle variation is referred to as PS.

A new generation of a product consists of these three sets of subsystems. It is called G_n and expressed by the union of the three subsets.

$$G_n = CS_{n+1} \cup ES_{n+1} \cup PS_{n+1} \tag{1}$$

With the given mathematical correlations, the percentage of those subsystems can be calculated that are subject to a certain type of variation. To do this, one of the three subsets refers to the totality of all subsystems of the new product generation.

The CV share is the percentage share of all subsystems of a new product generation developed by CV and is calculated as follows:

$$\delta_{CV,n}[\%] = \frac{|CS_{n+1}|}{|G_{n+1}|} = \frac{|CS_{n+1}|}{|CS_{n+1} \cup ES_{n+1} \cup PS_{n+1}|} \tag{2}$$

Analogous results for embodiment- and principle-variation-shares [16]:

$$\delta_{EV,n}[\%] = \frac{|ES_{n+1}|}{|G_{n+1}|} = \frac{|ES_{n+1}|}{|CS_{n+1} \cup ES_{n+1} \cup PS_{n+1}|} \tag{3}$$

$$\delta_{PV,n}[\%] = \frac{|PS_{n+1}|}{|G_{n+1}|} = \frac{|PS_{n+1}|}{|CS_{n+1} \cup ES_{n+1} \cup PS_{n+1}|} \tag{4}$$

The models and approaches discussed in the previous sections can help to assess projects in the product development process regarding innovative potential and development risk. The DMS example of Albers 2017 [16] already shows that principle variations in subsystems often lead to major problems during implementation. The extensive adaptations required as a result lead to a high development risk.
In addition, there is always a risk [17] for a developer if the principle used is new to him. If a development task is implemented by a developer or entrepreneur who already has experience and knowledge in the respective specific task area, the development risk is lower. However, if the developer has little or no experience in the task area, the development task tends to be riskier. The development risk therefore always depends on the context of the action system of which the developer is a part.

3. Methodology

In this paper, two case studies are analyzed retrospectively: A test bench for clutch friction linings and an actuator unit of a machine tool. In both cases the authors of this article have direct access to the systems. The analysis of each case example is done with the steps in Figure 4.

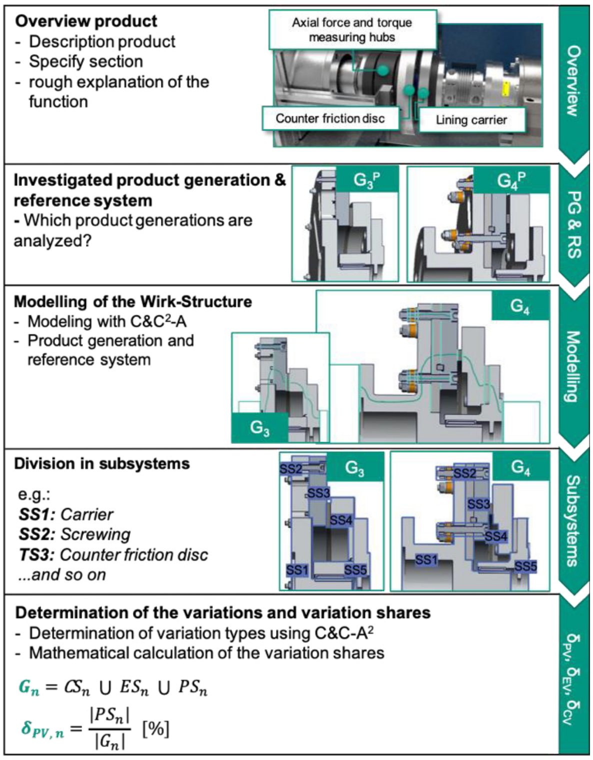

Figure 4: Overview procedure method of investigation

Overview product: The first step provides an overview of the product with a focus on the section to be examined later. Renderings and CAD sectional representations can be used here.

Investigated product generation and reference system: This step shows which product generation is compared and defines its reference system.

Modelling of the Wirk-Structure: For the product generation and the associated reference system, the Wirk-Structure is modelled. For this purpose, the system section, state and function are defined.

Division in subsystems: Now the product generation and the associated reference system are divided into subsystems, which are clearly numbered and named. Here it is recorded which WSP and CSS belong to which subsystem.

Determination of the variations and the variation shares: The various subsystems of the product generations under consideration are now compared with their reference system elements. The types of variation are to be identified with the help of modelling using the Contact-and-Channel-Approach.

The C&C^2-A-based indicators from the state of the art are used for this purpose. Once the variation types of the individual subsystems have been determined, it is possible to calculate the variation shares mathematically.

4. Results

4.1 Retrospective Analysis of Variations in PGE of a test bench

The dry friction test rig at the IPEK was used as a case study. Two product generations with a focus on the probes are examined in more detail within the framework of the investigation method.
The product generation investigated is the 4th generation test rig. The reference system consists of the third generation and its subsystems.
Figure 5 shows the detailed sectional views of the third and fourth generation probes.

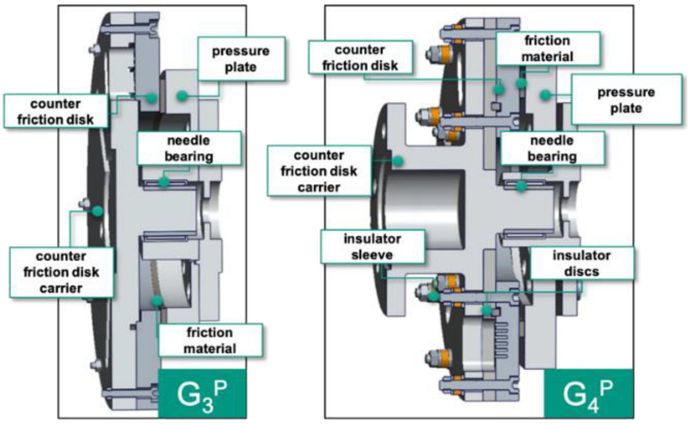

Figure 5: Sectional views of both probe generations

After initial modelling of the Wirk-Structure and subdivision into subsystems, the following types of variation were identified according to the criteria established by Albers in 2017 (see 2. State of the Art).

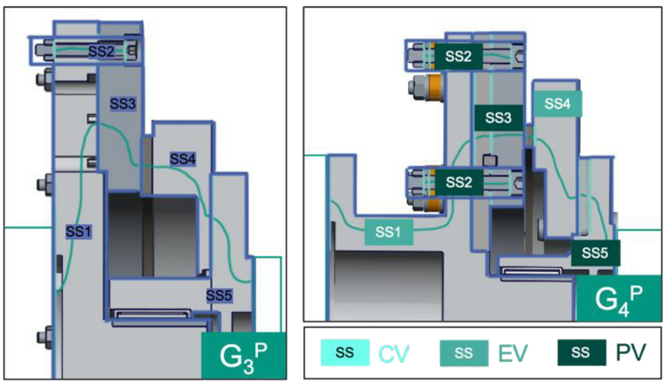

Figure 6: Initial Run - Overview of Variation Types

The mathematical model from the state of the art weights all subsystems in the calculation equally. The previous calculation should be extended and the different number of components in the different subsystems taken into account. The more CSS and WSP a subsystem has, the higher its weighting will be. The new weighting factor g_i^x describes the weighting of the i subsystems of variation type x and the following formula calculates the variation shares.

$$g_i^x, x \in \{CS_{n+1}, ES_{n+1}, PS_{n+1}\}, i \in \{1, \dots, |x|\} \qquad (5)$$

$$\delta_x[\%] = \frac{\sum_{i=1}^{|x|} g_i^x}{\sum_{j\in\{CS_{n+1},ES_{n+1},PS_{n+1}\}} \sum_{l=1}^{|j|} g_l^j} \qquad (6)$$

The carryover-, embodiment and principle variation shares are calculated as follows:

$$\delta_{CS,4} = 0\% \qquad (7)$$

$$\delta_{ES,4}[\%] = \frac{3 \cdot |\{SS1\}| + 5 \cdot |\{SS4\}|}{3 \cdot |\{SS1\}| + 18 \cdot |\{SS2\}| + 5 \cdot |\{SS3\}| + 5 \cdot |\{SS4\}| + 5 \cdot |\{SS5\}|} \approx 22\% \qquad (8)$$

$$\delta_{PS,4}[\%] = \frac{18 \cdot |\{SS2\}| + 5 \cdot |\{SS3\}| + 5 \cdot |\{SS5\}|}{3 \cdot |\{SS1\}| + 18 \cdot |\{SS2\}| + 5 \cdot |\{SS3\}| + 5 \cdot |\{SS4\}| + 5 \cdot |\{SS5\}|} \approx 78\% \qquad (9)$$

The C&C^2-A detail depth was now varied. The number of elements of the bolting was reduced and the insulator disc and hollow shaft/counter friction disc were modelled together. Figure 7 shows the new modelling in comparison to the initial run.

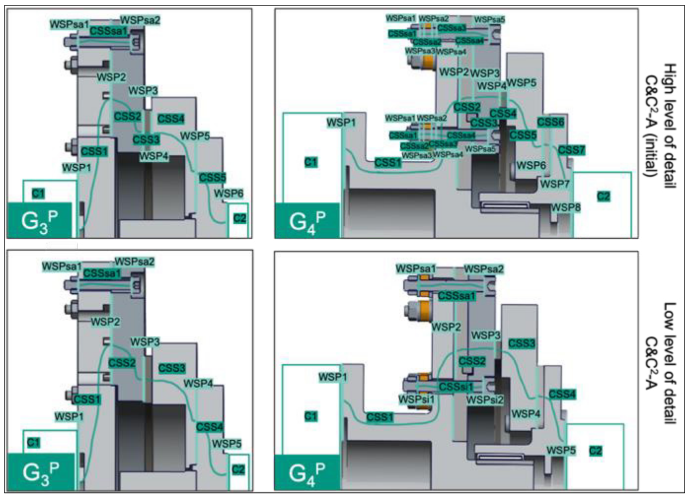

Figure 7: C&C^2-A Modelling in comparison

The subdivision into subsystems remained the same as in the initial run. The following table shows a comparison of the identified types of variation.

Table 1: Overview variation types

	High level of detail C&C²-A (initial)		Low level of detail C&C²-A	
Subsystem	**Variation type**			
Subsystem 1	Embodiment Variation	EV	Embodiment Variation	EV
Subsystem 2	Principle Variation	PV	Principle Variation	PV
Subsystem 3	Principle Variation	PV	Embodiment Variation	EV
Subsystem 4	Embodiment Variation	EV	Embodiment Variation	EV
Subsystem 5	Principle Variation	PV	Embodiment Variation	EV

Subsystem 3 and subsystem 5 were identified as an EV at the lower C&C²-A detail depth, since the insulator disc and the hollow shaft/counter friction disc were now modelled together. Subsystem 2 was still identified as a principle variation. In addition, the modified modelling shifts the weighting of the SS, even for those subsystems, where the variation type is unchanged.
The table compares the calculated variation shares with the results of the initial run. It is noticeable that a reduced modelling depth results in a lower share of principle variations. The strong increase of the embodiment variation share is mainly due to the newly identified variation of SS 3&5 as well as the lower weighting of SS2.

Table 2: Variation of the parameter C&C²-A – Variation shares

	High level of detail C&C²-A (initial)	Low level of detail C&C²-A
Variation type	**Variation share**	
Carryover Variation	0 %	0 %
Embodiment Variation	22 %	67 %
Principle Variation	78 %	33 %

The procedure was again performed with more subsystems. Figure 8 shows the new subdivision compared to the initial run.

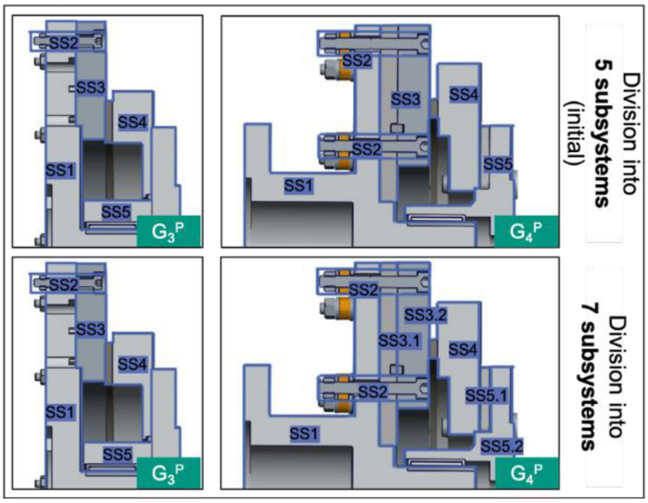

Figure 8: Comparison of the SS division

The C&C²-A modelling remained the same as in the initial run. The following table shows a comparison of the identified variation types.

Table 3: Variation of the Parameter Subsystem - Overview of Variation Types

Division into 5 Subsystems (initial)			Division into 7 Subsystems		
Subsystem	**Variation type**		**Subsystem**	**Variation type**	
Subsystem 1	Embodiment Variation	EV	Subsystem 1	Embodiment Variation	EV
Subsystem 2	Principle Variation	PV	Subsystem 2	Principle Variation	PV
Subsystem 3	Principle Variation	PV	Subsystem 3.1	Principle Variation	PV
			Subsystem 3.2	Embodiment Variation	EV
Subsystem 4	Embodiment Variation	EV	Subsystem 4	Embodiment Variation	EV
Subsystem 5	Principle Variation	PV	Subsystem 5.1	Principle Variation	PV
			Subsystem 5.2	Embodiment Variation	EV

Only subsystem 3 and 5 had an influence on the changed variation shares, as these were further separated into subsystems 3.1 and 3.2 as well as subsystems 5.1 and 5.2 in the variation. As the new insulator discs with counter friction disc (SS3) and hollow shaft (SS5) were in one subsystem during the initial run, these subsystems were identified as principle variations. Due to the new subdivision of the subsystems, however, only SS3.1 and SS5.1 have been identified as principle variations and SS3.2 and SS5.2 are embodiment variations.
The table compares the calculated variation shares with the results of the initial run.

Table 4: Variation of the parameter subsystem - Variation shares

	Division into 5 subsystems	Division into 7 subsystems
Variation type	**Variation share**	
Carryover Variation	0 %	0 %
Embodiment Variation	22 %	37 %
Principle Variation	78 %	63 %

In this case it is noticeable that a larger number of subsystems results in a lower share of principle variations. It became apparent that with only one additional element in a large subsystem, this is identified as a principle variation according to criterion 3. By further subdividing the subsystem into smaller subsystems, new subsystems as parts of a formerly bigger subsystem could be identified as embodiment variation because they are considered separately.

4.2 Retrospective Analysis of Variations in PGE of an actuator unit of a machine tool

Using the same procedure, the actuator of a laser machine from a machine tool manufacturer was examined. Within this contribution CAD data are not depicted due to confidentiality. However, the wirk-structures are shown as 2D-layout. The carriage unit was initially divided into 6 subsystems and modelled. The variation components were then calculated.

Figure 9: Trulaser 1030 fiber (Trumpf 2019)

In the next step, as with the probe, the C&C^2-A depth of detail was varied. One support point was modelled by an additional CSS. The modelling depth of the guide rails was also increased. Figure 9 shows a principle view of the new modelling compared to the initial run.

The division into subsystems remained the same as in the initial run and table 5 shows the identified variation types in comparison.

Table 5: Comparison of the C&C^2-A Modelling

	Low level of detail C&C^2-A (initial)		High level of detail C&C^2-A	
Subsystem	Variation type			
Subsystem 1	Principle Variation	PV	Principle Variation	PV
Subsystem 2.1	Embodiment Variation	EV	Embodiment Variation	EV
Subsystem 2.2	Embodiment Variation	EV	Principle Variation	PV
Subsystem 2.3	Principle Variation	PV	Principle Variation	PV
Subsystem 3	Principle Variation	PV	Principle Variation	PV
Subsystem 4.1	Carryover Variation	CV	Carryover Variation	CV

Subsystem 2.2 was identified as a principle variation at the higher C&C^2-A detail depth, since the number of elements has increased.

The carryover variation share has increased in the new modelling in comparison to the initial run, since the only subsystem with carryover variation (SS4.1) with 4 elements is weighted more heavily. The embodiment variation share decreases, while the principle variation share increases, since a support point (SS2.2) was no longer identified as an EV due to newly modeled elements and was weighted more heavily at the same time.

In order to investigate the influence of the division of the subsystems, the system was subsequently subdivided into four subsystems instead of six.

Table 6: Comparison of the subsystem division

Division into 6 subsystems (initial)			Division into 4 subsystems		
Subsystem	Variation type		Subsystem	Variation type	
Subsystem 1	Principle Variation	PV	Subsystem 1	Principle Variation	PV
Subsystem 2.1	Embodiment Variation	EV	Subsystem 2	Principle Variation	PV
Subsystem 2.2	Embodiment Variation	EV			
Subsystem 2.3	Principle Variation	PV			
Subsystem 3	Principle Variation	PV	Subsystem 3	Principle Variation	PV
Subsystem 4.1	Carryover Variation	CV	Subsystem 4	Principle Variation	PV

Table 6 shows the new subdivision and the respective identified variation types. Since the support points are now regarded as a subsystem, the subsystem as a whole was identified as a principle variation. The guide rails were now also identified as principle variation, since the entire subsystem was compared with the previous generation instead of individual rails.

Thus, a reduction in the number of subsystems led to an increase in the principle variation share.

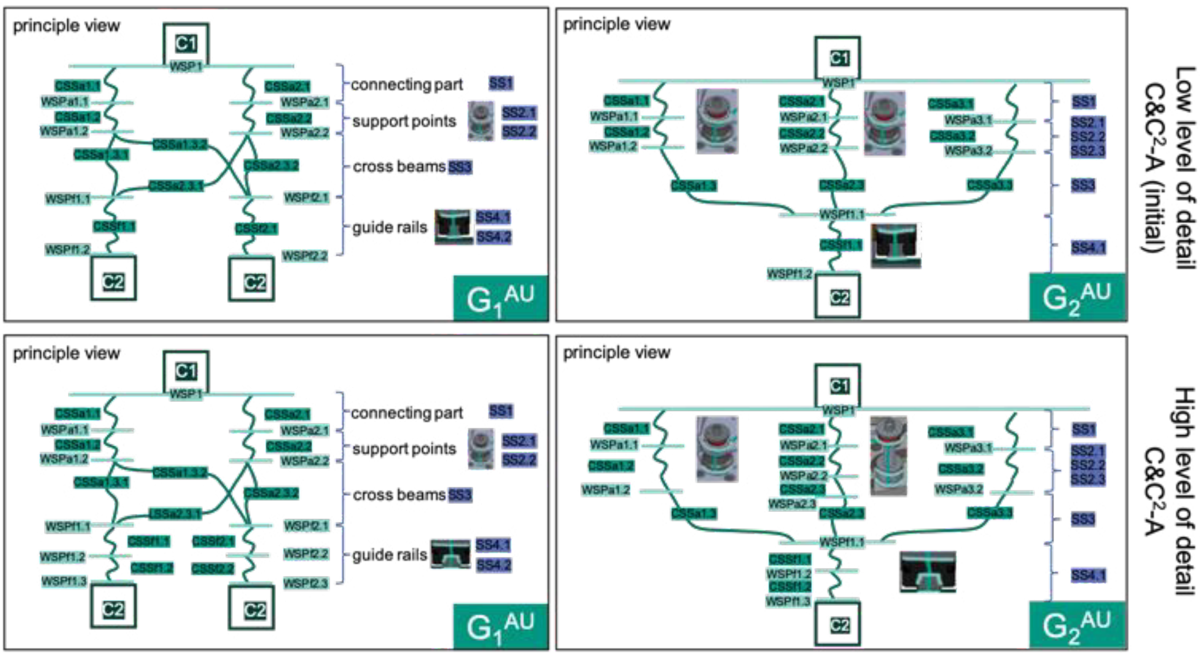

Figure 10: Simplified C&C^2-A Modelling in comparison

5. Discussion & Conclusion

The investigations show how influencing factors affect the calculation of the variation share. The first case study was a test bench. A less detailed modelling with C&C^2-A resulted in a lower principle variation share, i.e. a change in the number of WSP and CSS compared to the reference system was less frequent. However, the modelling depth of the C&C2-A influenced the variation shares not only by the type of variation identified, but also by the weighting of the respective subsystems. If subsystems are weighted differently according to complexity and this weighting is determined on the basis of the number of elements, the depth of detail of the C&C^2-A modelling has a decisive influence on the result. A larger number of subsystems always resulted in a lower principle variation share.

The investigation method was also examined on a flatbed laser machine of a machine tool manufacturer. In this case, a higher level of detail in modelling with C&C^2-A as well as a lower number of subsystems resulted in an increased principle variation share.

The choice of the respective reference system is decisive for the identification of a variation. Thus, a previously non-existent component can be identified as CV, EV or PV, depending on which reference system element it is compared with.

The investigated product generations were always considered retrospectively within the scope of the investigation. The question arises as to which level of detail of the C&C^2-A modelling would be appropriate. While this might be answerable during a development process, it is hard to determine retrospectively what knowledge was available about the embodiment-function-relation at what point in time and what subsystem structure this was associated with. Hence, contradictory results may appear possible in the retrospective analysis.

In summary, subsystems were no longer identified as principle variations in a less detailed modelling with C&C^2-A when a change in the number of WSP and CSS was no longer apparent. In addition, the C&C^2-A modelling had an effect on the weighting of the individual subsystems in the calculation. A higher number of subsystems again reduced the principle variation share, since components of the SS identified as PV can be identified as CV or EV with a more detailed subdivision. The choice of the modelling depth with C&C^2-A, the division in subsystems, the reference system element and the type of weighting in the calculation are therefore decisive influencing factors.

6. Outlook

Answering the following questions is interesting for future research:

- What level of detail of C&C^2-A modelling is appropriate at a certain point in the development process by reflecting the knowledge of the embodiment-function-relation? What subsystem structure is this based on?
- Is it possible to establish fixed modelling rules for carrying out analyses similar to the one presented, that will work for each case?
- If so, how can these modelling rules be formulated in an understandable way so that as few questions as possible remain unanswered for the user?

A meaningful determination of the variation shares is important for a benefit in the project assessment and can help to identify development risks or innovation potentials in advance and to classify them quantitatively. Furthermore, it is important to interpret the results of the research method correctly. For example, a high principle variation share in different companies can have a different influence on development risks due to the prior knowledge of the employees. Since the research method in the case studies could only be applied retrospectively, the collection of information in the ongoing process should be researched in the future.

Currently, the focus of application of the C&C^2-A approach is on mechatronic systems, which thereby defines the potential scope of the presented analysis procedure. Extending the scope of application of the C&C^2-A approach is also subject to further works.

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