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PGE - PRODUCT GENERATION ENGINEERING - CASE STUDY OF THE DUAL MASS FLYWHEEL

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1. Introduction and motivation

Innovations are the result of transferring recognized customer value (product profile) into a new product (invention) and distributing and establishing that product in the market (diffusion) [Schumpeter 1934]. In opposite to the sometimes presented opinion stating that innovations are based on sudden inspirations, innovation is a hard and time-consuming work. In many cases an aha-moment occurs, but it arises from exhaustive dealing with the given task. Case studies show that the first product generation often lack the amount of maturity necessary to be thriving in the market. Hence products are often engineered further in subsequent product generations, which then lead to true success.

The following chapters will first highlight PGE - Product Generation Engineering and related research fields. In the course of enhancing the approach of PGE and making it applicable for managing development processes and innovation work the main part of the article presents a case study on multiple generations of the dual mass flywheel (DMF). By describing the different types of variation in the DMF generations with C&C²-A - the Contact-and-Channel-Approach, the following questions are adressed in particular:

- How can individual subsystems be designated to variation of principal, variation of embodiment or variation in order to carry over?
- What challenges come along with the different types of variation?

Finally an outlook on current research topics is given.

2. State of the art

2.1 PGE - Product Generation Engineering

Classic design methodology assumes three types of engineering projects which are new construction, adjustment and variant construction. They are differentiated by the following criteria: Degree of novelty, tentativeness with regard to dominating conditions and the chance of using well-known and prevailing solution principles [Pahl et al. 2013]. Contrary to this classification of development projects, new literature more and more emphasizes that today products are barely completely new developed. Due to economical and risk analysing thoughts realization of the intended product's functions and features should be achieved by modifying already existing proved solutions as little as possible [Deubzer and Lindemann 2009], [Eckert et al. 2010]. Eckert hints at most development projects being enhancements of products which are already in the market. Thus the majority of products result from adjustment. Properly working parts and subsystems of more complex systems are maintained as far as possible to minimize technical newness, potential risks and necessary investments e.g. for manufacturing facilities

[Eckert et al. 2010]. Regarding a whole new product the degree of novelty is made up not just of the number of subsystems that have been newly developed but also of optimizing functions and features of established subsystems and assemblies or extending their application domain [Albers et al. 2015c]. Using the Kano Model [Kano et al. 1984] customer value and other requirements in different dimensions, e.g. functionality and cost-benefit-aspects can be divided in basic, performance and fascination requirements. These requirements are changed in the process of product development and have to be fitted to every product generation regarding actual market conditions, restrictions and needs [Bailom 1996]. Figure 1 shows the model of product life cycles [Wesner 1977] and the technology S curves [Burgelman and Wheelwright 2004]. Looking at the S curves it becomes obvious that success in the market and thus innovation of newly engineered product generations can not only be achieved by often focused transitions from one technology to another but also with improvements of already used technology.

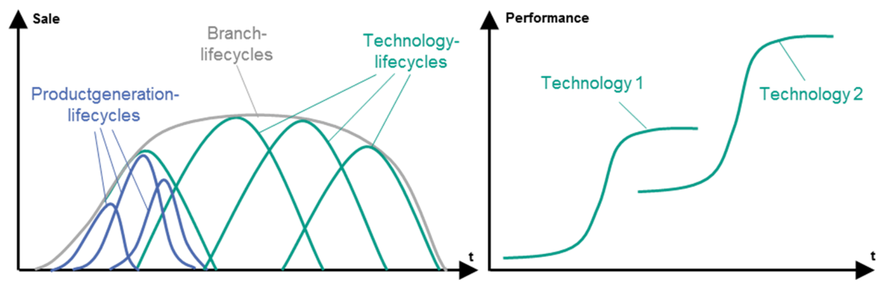

Figure 1. left: model of product life cycles [Wesner 1977] right: technology S curves [Burgelman and Wheelwright 2004]

Developing a new generation of technical products by combining specific variations, in order to carryover (CV) from existing products on one hand and in order to develop new on the other, is understood as PGE. The new development of subsystems can be done in two ways: Either by the activity of embodiment variation (EV) or by the activity of principle variation (PV), meaning the use of other respectively new solution principles for the entity. Whereas principal variation is always accompanied with embodiment variation. One or more existing products defining the new product are referred to as reference products [Albers et al. 2015b]. Therefore reference products are one or more precursory products or products from competitors, which are used as base for the development of a new product generation and serve as base for the fundamental structure. The newly developed shares of a new product generation should create functions and features which realize difference and thus enable differentiation of the new product from the reference product(s) [Albers et al. 2015b].

Consecutively the essential relations of PGE are described by mathematical expressions. The purpose of the mathematical modelling is to ease strategy and conduct of product development projects by evaluating and planning the shares of a) variation in order to carryover from a reference product b) subsystems which are newly developed by the activity of embodiment variation and c) new development starting with a principle variation. Taking into account current circumstances, e.g. concerning the market or the own company, product development processes can be designed individually by choosing the appropriate types of variation after estimating their importance and associated risks [Albers et al. 2015a].

A new product generation ($G_{\mathrm{n+1}}$) is consisting of subsystems (SS) that are the result of variation in order to carryover (CS) as well as SS that are new developed with embodiment variation (ES) or principle variation (PS) [Albers et al. 2015b]:

$$\boldsymbol{CS}_{\mathrm{n+1}}\left\{\mathrm{SS} \mid \mathrm{CV}_{(\mathrm{SS})}\right\};\ \boldsymbol{ES}_{\boldsymbol{n+1}}\left\{\mathrm{SS} \mid \mathrm{EV}_{(\mathrm{SS})}\right\};\ \boldsymbol{PS}_{\boldsymbol{n+1}}\left\{\mathrm{SS} \mid \mathrm{PV}_{(\mathrm{SS})}\right\} \tag{1}$$

Using (1) the composition of a new product generation can be formulated as follows:

$$\boldsymbol{G}_{n+1} = \boldsymbol{CS}_{\boldsymbol{n+1}} \cup \boldsymbol{ES}_{\boldsymbol{n+1}} \cup \boldsymbol{PS}_{\boldsymbol{n+1}} \tag{2}$$

In order to that the share of subsystems that are varied in order to carryover ($\delta_{\mathrm{CV}\ n+1}$) of a product generation is defined as:

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

In the same way the shares of subsystems resulting from embodiment variation ($\delta_{\mathrm{EV}\ n+1}$) and of those created by principle variation ($\delta_{\mathrm{PV}\ n+1}$) can be specified. The values δ chosen in the phase of planning a development project are already vital parameters for the development process. Potentially occurring differences between the planned and in real-time tracked values for δ are considerable for risk analysis and validating a new product generation [Albers et al. 2014a]. Examples for PGE shown hereafter are the Porsche 911 and printing machines by Heidelberger Druckmaschinen AG (cf. Figure 2).

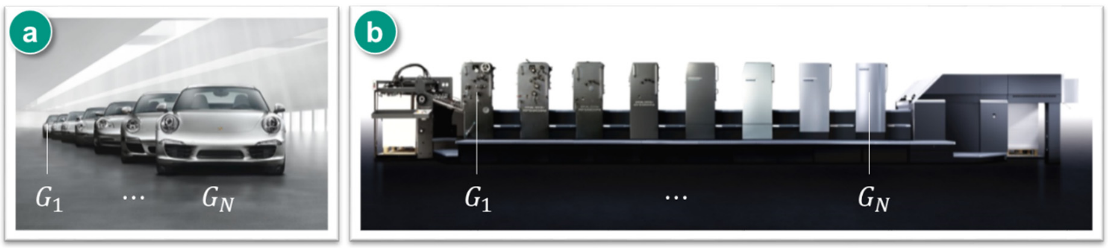

Figure 2. PGE from G_1 to G_N using the example of products from Porsche (a) and Heidelberger-Druck (b) (according to [Albers et al. 2015b])

A broad empirical study showed products being developed in generations across various industrial sectors and company sizes [Albers et al. 2014b]. Approaches to distinguish the different types of variation and describe them in more detail are required though. For this purpose the Contact-and-Channel-model is suitable and will be presented below.

2.2 C&C²-A Contact and Channel Approach

Making the PGE approach applicable for managing development processes requires appropriate product modelling methods which can support the development of new product generations by the three types of variation. Based on theoretical considerations, empirical findings and by taking into account different modelling techniques for functional product structures, product embodiments and - more or less - the dependence between them (e.g. [Koller 1994], [Weber 2008], [Deubzer and Lindemann 2009]) [Albers and Wintergerst 2013] introduce C&C²-A. C&C²-A connects the conceptual description of technical systems by functions with the constructive description of embodiment. Therefore the following elements are used [Matthiesen 2002], [Albers and Wintergerst 2013]:

- Channel and Support Structures (CSS)
- Working Surface Pairs (WSP)
- Connector (C)

Figure 3 illustrates the elements and their application using the powertrain of a modern vehicle with the function "transmitting torque from combustion engine to the wheels and adjust rotational speed" as an example. Simultaneously the figure shows important subsystems of power trains and their placement, including the coupling system with torsional damper. A small number of different modelling elements and the applicability on different levels of abstraction are i.a. advantages of C&C²-A. As a tool C&C²-A can support both analysis starting with the embodiment and ending up with conceptual functions and synthesis beginning with functions and – by adding and removing contacts and channels – resulting in definite embodiment, which makes it very promising for use in the PGE context. Connectors allow embedding of the considered system into its environment. They are linked with the contacts at the system boundary [Albers and Wintergerst 2013].

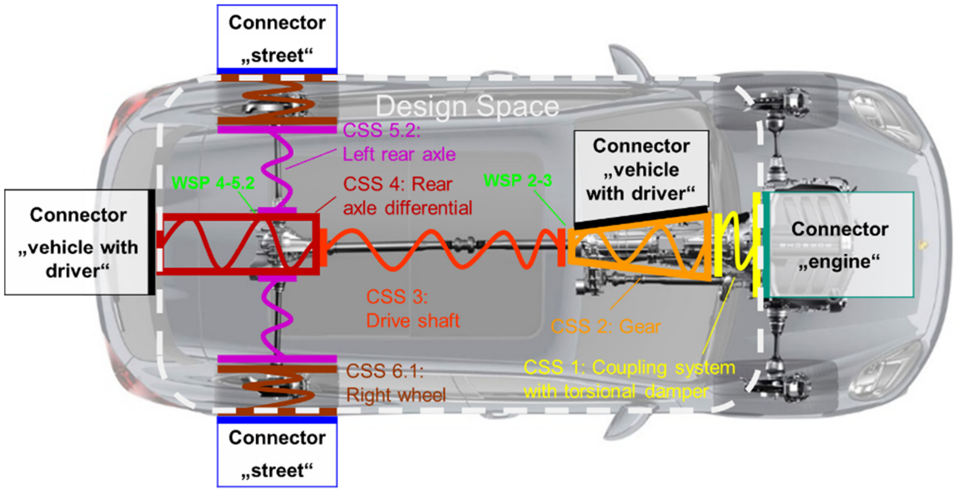

Figure 3. Description of a powertrain with function "transmitting torque from combustion engine to the wheels and adjust rotational speed" with the C&C²-A by using the elements "WSP", "CSS" and "Connector" (due to clarity not all WSPs numbered) (Own work, following [Albers and Wintergerst 2013])

3. Aim and methodology of research

Making the approach of PGE applicable for manging product engineering processes and their associated risk by using the mathematical model for specifying and controlling the shares of the different variation types is an important objective of further research in the field of development and innovation management. Therefore a way to designate individual subsystems to the variation types is necessary as well as further knowledge about the challenges accompanying the different types of variation. Thus the following research questions are subject of this article :

- How can individual subsystems be designated to variation of principal, variation of embodiment or variation in order to carry over?
- What challenges come along with the different types of variation?

Generations of existing products are examined as case studies to answer those questions. Changes in the generations, which can obviously be designated to a certain type of variation, are described by an appropriate modelling tool. Then we check whether the changes in the descriptions of the different product generations allow for the derivation of a rule how individual subsystems can be designated to the different types of variation by using the modelling tool for analysis. As shares of variation have to be managed across different stages of the development process and different levels of concretisation, including but not only the activities of detecting ideas and modelling principle solution and embodiment, a modelling tool to perform the intended analysis must be capable of fulfilling these requirements. C&C²-A is used for this purpose. In addition to the analysis of the variation types the challenges of the related development processes are outlined.

This article presents a case study on multiple generations of the dual mass flywheel (DMF). Using the DMF as an example is very convenient because it has experienced several types of variations in different subsystems since the development of the first generation over 20 years ago and it is still developed in further generations. Another advantage of choosing the DMF as a first example is that the first author of this contribution participated in the development of multiple DMF generations for several years. In the beginning as supervising person in the company and as research partner subsequently. Hence information on the challenges which occurred in the development processes are available in more detail than usually. The underlying data and processes are completely from PGEs performed in real environments. Due to the amount of information it is not possible to cover all DMF generations and all subsystems in this article. Recent generations and subsystems which are not covered in this contribution will be part of subsequent works.

4. Case study on the dual mass flywheel

The DMF is a subsystem in the powertrain of modern motor vehicles, which contributes vitally to their quality concerning noise vibration harshness (NVH). Thus it has become standard for many vehicles. To date more than 110 million DMFs of different product generations have been installed. As follows the product profile (cf. [Braun 2013]) and the engineering of the first and of succeeding generations as examples for PGE are discussed in further detail.

4.1 Product profile

Caused by the 1979 oil crisis the demand for vehicles with reduced fuel consumption grew. The OEMs responded to this with adjusted vehicle concepts. The Bayerische Motoren Werke AG (BMW) for example introduced the eta concept with energy efficient engines and overdrive. Main goal was engine operation with low revolutions per minute (rpm) and taking advantage from the low specific fuel consumption in this operating range. However running with low rpm leads to increased rotational non-uniformity and thus to greater NVH problems, which are not acceptable. Those problems could not be handled with standard torsional vibration dampers that were used by this time. Hence the following product profile for the new development of the coupling system arose:

"We need a system which makes rotational non-uniformities, occurring in the power train, caused by combustion engines operating with low rpm, controlable concerning NVH."

4.2 Engineering of the first product generation

The spring rate of the technological exhausted, in the clutch disk integrated torsional damper (cf. left in Figure 4) had been decreased continuously. Due to limits of the design space further reduction was not possible. Therefore the development of a new principal solution was intended; the approach was extension of the design space. Adding the flywheel to the design space opened up new possibilities. The relevant torsional natural frequency of the powertrain is influenced by the inertia of the gear wheels, the spring rate of the torsional damper and the stiffness of the powertrain itself. Gear and other parts of the powertrain are not included in the design space for the DMF because other stakeholders (OEM, suppliers) are responsible for them and thus they cannot be varied. Following machine dynamics the positive direction of development results from increasing gear inertia and reducing the spring rate of the torsional damper. Taking into account that the moment of inertia (MOI) of the gear defines the gear change forces, increasing of the MOI of the gear wheels for this operating status is excluded. This constraint has to be considered when searching for new solutions. Furthermore the embodiment of a solution is obviously predefined by the given installation space in the clutch case, the dimensioning of the clutch and the overall size of the flywheel. The new solution principle, realized in the first DMF generation (cf. right in Figure 4) is based on the separation of the engine flywheel (Figure 4: I) into two parts (primary (Figure 4: II) and secondary flywheel (Figure 4: III)) with bearings (Figure 4: IV) and compression springs (Figure 4: V) in-between. The clutch pressure plate is connected to the secondary flywheel. The clutch disk can now be rigid, i.e. the originally integrated compression springs are removed. The WSPs where the gear change function is realized are now between secondary flywheel and one friction lining of the clutch disk and between the pressure plate and the second friction lining of the clutch disk. This topology of the coupling system with DMF guarantees that only the original MOI of the gear is effective when the clutch is opened to separate the rest of the powertrain from the engine for changing gears; thus the gear change forces do not increase. However when the clutch is closed the natural frequency of the power train can now be reduced significantly, because in machine dynamics the secondary flywheel is not assigned to the inertia of the gear. Thereby due to resonance displacement notably supercritical vibration isolation in operation is achieved so that rotational non-uniformities of the combustion engine are transmitted strongly reduced to the gearbox input. Figure 4 displays the two parts of the separated flywheel with - according to the state of art - statically determined bearings (Figure 4: IV). The springs of the torsional damper (Figure 4: VI) were carried over in the basically same arrangement like in the original clutch disk but placed on a greater diameter between the two new flywheels (Figure 4: V). In this way a higher capacity of the springs and a further slight decrease of the natural frequency could be attained. The resulted product showed major potentials. The demand of the product profile for significant reduction of rotational non-uniformities in the operating range could be fulfilled.

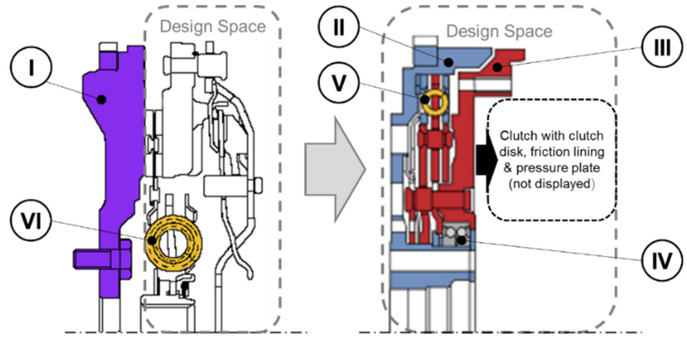

Figure 4. Design space for conventional torsional damper and extended design space for the first generation of DMF [LuK 2009]

Though, especially in start/stop procedures but as well during driving with low engine speed operation close to resonance could occur, resulting in serious NVH and fatigue problems. Also due to the statically determined mounting of the two flywheels gyroscopic forces caused great loads in the WSPs of the bearings leading to problems with service life. Another challenge was presented by the carried over arrangement of the springs. Because of the greater diameter of the placement the springs are pushed outwards by centrifugal force and get in contact with the spring windows (solid-on-solid-WSP). Increased deflections of the springs in consequence of the improved isolation effect caused heavier wear in den WSPs. Those were covered with the second DMF product generation.
As follows changes in subsequent product generations will be discussed exemplarily for the subsystem of the bearing between the two flywheels. However this method is fully transferable and can as well be reproduced using other subsystems. For example was a lubrication introduced for the solid-solid-WSPs of the spring system and the performance potential was increased significantly through strong embodiment variation by using bow springs. This will be subject to a further article.

4.3 PGE described with C&C²-A with the DMF bearing as example

The DMF product generations are displayed in Figure 5. With the focus on the DMF bearing the types of variation in the different product generations will be designated. The challenges of the associated engineering process will be discussed and the solutions will be analysed with C&C²-A.

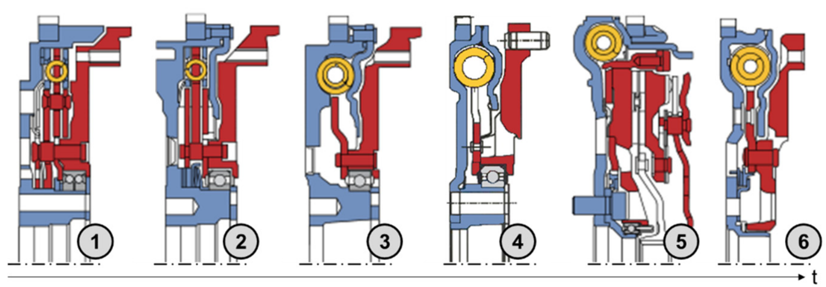

Figure 5. DMF product generations from 1985 to 2009 (according to [LuK 2009])

Due to the statically determined mounting between the two masses of the flywheel (Figure 6: I) especially coriolis forces lead to great loads in the WSPs of the rolling element raceways in the bearings and thus to pittings. To avoid loads resulting from the inflexible connection of the secondary flywheel with the primary flywheel a considerable principle variation was made. By removing WSPs of the bearing (cf. Figure 6) a statically indetermined bearing with a tilt degree of freedom was established in the second generation (Figure 6: II). Though contrary to the state of the art and doctrine for the design of bearings the chosen solution was convincing in validation, the problem was solved. To reduce heat input to the bearing and by that impairment of the lubrication two covers made of high temperature resistant polymer with a small coefficient of thermal conductivity wrapping the bearing (Figure 6: III) were introduced as new WSPs and CSSs. Additionally a new lubricating grease which met the unusual operating conditions (oscillating motion) was developed for the bearing (Figure 6: IV).

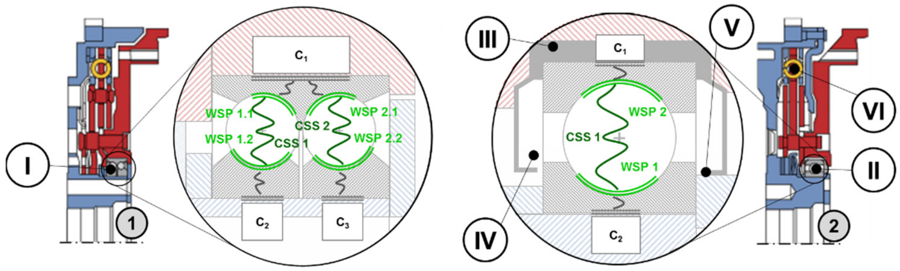

Figure 6. WSPs, CSSs and Connectors for the first and second presented DMF product generation

At the same time the purposeful design of the WSP between the inner ring of the bearing and the cover (Figure 6: V) enabled a specific adjustment of the base friction besides the sealing function. This provides another degree of freedom for adapting the dynamic properties of the DMF to the engine-gear-vehicle-combination of the superordinate system. Moreover a lubrication of the springs was used for the first time (Figure 6: VI).

The new bearing arrangement worked well and was carried over to the third displayed product generation (variation in order to carry over). Therefore there were no changes of WSPs and CSSs in this area. Substantial motivation for this procedure was to take no new risks in the development process concerning this subsystem and optimize other subsystems first. The focus while engineering this product generation was on a further spring rate reduction for the torsional damper. For this purpose the originally straight-line springs were substituted (embodiment variation) by bow springs of 90° first and nearly 180° later on. The lubrication grease in the damper had to be newly developed though because centrifugal forces caused segregation of soap and base oil.

For the fourth presented DMF product generation the bearing was carried over again. To optimize the cost structure essential parts of the DMF were redesigned for manufacturing by deep drawing in this generation.

The lasting success of the DMF-principle created a demand for middle class vehicles which typically have a front-wheel-drive-topology. The challenge for the fifth displayed product generation is therefore the strict limitation of the design space as engine and gear box have to be placed between the front wheels. To get along with the particularly narrow design space in the axial direction the subsystems of the DMF and the clutch system had to be nested into each other (cf. Figure 7). Among others this lead to the requirement to reduce the outer diameter of the DMF bearing significantly. In terms of PGE this is a strong variation of embodiment. The mounting principle and therefore the number and the basic arrangement of WSPs and CSSs was maintained (cf. Figure 7) while the geometric dimensions changed and the load rating decreased to only approximately 20% compared to the reliable solution from the preceding product generations.

Temperature load and the smaller amount of lubricant in the bearing resulted in lubrication failure and finally bearing breakdown. Therefore the bearing was constructed specifically. The approved solution from the previous product generation with a polymer cover (Figure 7: I) was adjusted to establish a barrier for thermal conduction between the outer ring of the bearing and the secondary flywheel on the one hand and to amplify the amount of lubricant available to the bearing by shaping a reservoir (Figure 7: II) in the cover on the other hand. Moreover a high temperature lubrication grease for the DMF bearing was developed in validation tests on a specially built test bench. Thereby a trustworthy solution for the bearing task could be found. The integration of the screw connection to the crankshaft (Figure 7: III), which had been made by the engine manufacturer until this point, axial fixing of the bearing (Figure 7: IV), redesigning and the fastening of the clutch cover (Figure 7: V) and sealing the channel of the bow springs (Figure 7: VI) presented additional challenges. The overall solutions demonstrates that severe embodiment variation also leads to great challenges, especially regarding hedging.

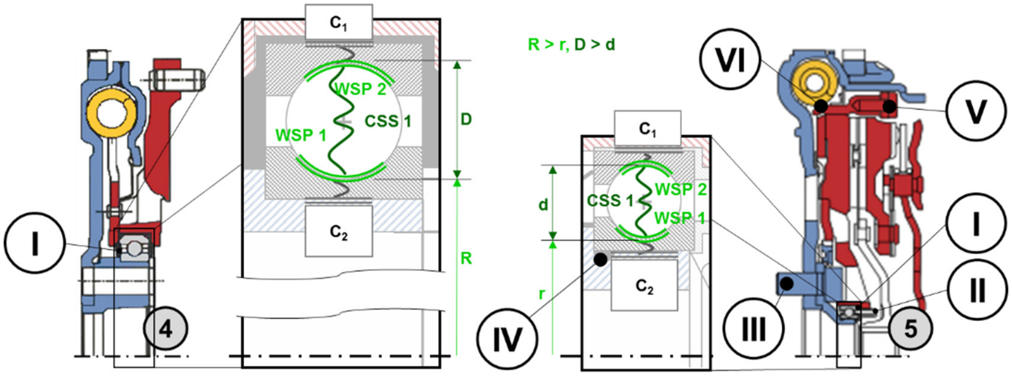

Figure 7. Difference in dimensions of WSPs and CSSs between fourth and fifth examined product generation due to embodiment variation

Constant cost pressure in the automotive sector naturally results in corresponding requirements in the system of objectives for the engineering of DMF generations. The changeover to a plain bearing (Figure 8: I) in the sixth presented generation can be seen as an example for a solution idea which was developed for cost reduction reasons mostly. It is again a principal variation that has to be seen in the context of the whole system and changes again the arrangement of WSPs and CSSs of the subsystem (cf. Figure 8).

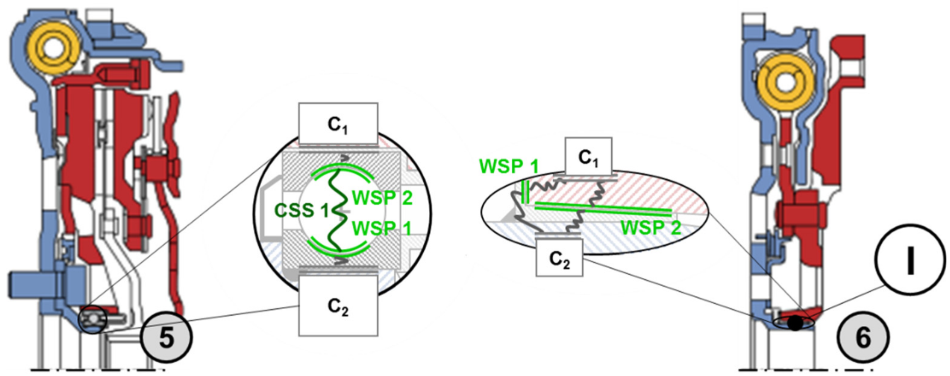

Figure 8. Once more changes in WSPs and CSSs in course of principal variation for the subsystem of the DMF bearing

Particular challenges emerge from the modified friction behaviour and the considerable more critical transmission of axial forces in the related WSPs when opening the clutch. Among others an increased base friction occurs which has significant influence on the isolation effect and thus has to be regarded and checked in the course of the individual adjustment of a DMF for a certain use-case. Depending on the use-case the issue of sufficient service life has to be considered as well. Engineering the plain bearing solution was again a great challenge and accompanied by intense verification and validation activities. The found solution could not be adapted to all scopes whereby today the plain bearing solution as well as rolling bearing solutions are used in parallel to each other for different application scenarios.

5. Discussion and outlook

Summarizing the case study, the following observations can be derived in the first place:

- The shown principle variations have always been accompanied by changing the number of WSP and CSS. The principle variations were also always associated with major development challenges in the technical implementation.
- The basic solutions for the WSP and CSS have been maintained for embodiment variation and new solutions were found by the variation of shape and arrangement. This is also represented in complex development challenges.

Looking at subsystems which were carried over from one generation to another it becomes apparent that they were affected by principal or embodiment variation of other subsystems, if they were connected to them. An example is the reduced axial length of the bearing seat in the second shown generation. Thus we can draw the following conclusion:

- For a variation in order to carry over the WSP and CSS remained mostly unchanged. Variations are made on WSP of the adjacent subsystems (connectors).

Refering to the research questions asked in section 3, we state:

- Most likely C&C²-A provides a way to designate individual subsystems to the different variation types of the PGE approach by using the observations above as criteria.
- Both, variation of principle and embodiment variation may involve major challenges for the development process

Searching for potential influencing factors on the associated risk for the development process the integration of the screw connection to the crankshaft into the fifth generation and the necessary validation activities suggests the following assumption:

- The risk increases if the reference product was not developed within the same team or company, as necessary knowledge is initially not available for the development process.

Through further empirical studies the made observations have to be verified and included in the theory of PGE. Reference products and characteristics of them, which are important influence factors for the development process (e.g. the relation between the team or company that developed the reference product and the team or company of the current development process), have to be described in more detail by future research. Besides upcoming works should investigate and determine additional influence factors on the risk coming along with the different types of variation and may define the term "radical innovation" more precisely in the context of PGE.

The shown variations in this case study, e.g. on the bearing, have only a small share in the entire vehicle, but can have far-reaching effects if the function is not fulfilled. Thus for future research the question arises how the risk, coming along with principle and embodiment variation, can be made transparent in higher system levels.

Moreover, it was observed that, especially for principal and embodiment variation, extensive verification and validation scopes were necessary. In the most product generations iterative improvements through various development generations are needed to define the final solution. Different maturity levels can be definded within the development of individual product generations, hence. Transferring the PGE approach to individual development processes this can be understood as a sequence of development generations (cf. Figure 9) where the same types of variation (principle, embodiment, carry over) are used. Extending the PGE approach in this way will be subject to further works, too.

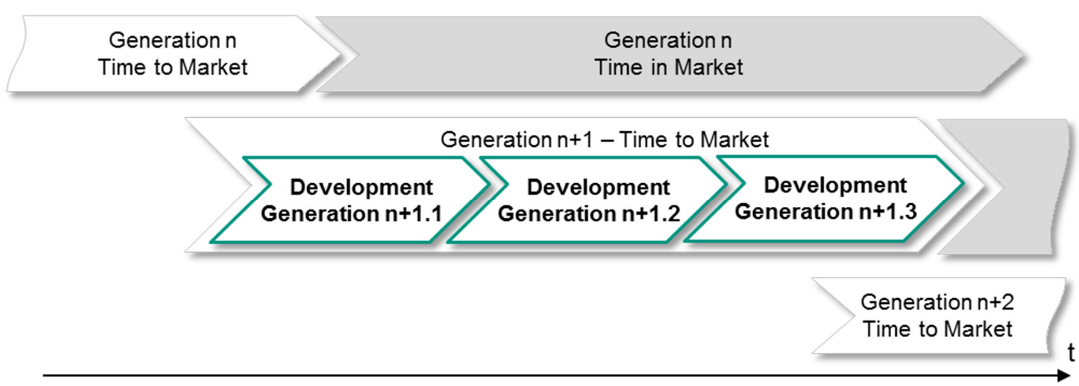

Figure 9. Development Generations in PGE

Thus, for example in the early stages it can be purposeful to use a high share of carryover subsystems from previous product generations and develop only the critical subsystems prototypically new in order to get information about the feasibility. In following contributions it will be examined how these development generations can be described as part of a product development process. In addition, the case study will be presented in further publications in order to describe other aspects of the product generation development (e.g. development processes or patent strategies). Based on gained results methods for decision support and managing development process using the PGE approach will be devised.

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