This paper was presented at The XXXIII ISPIM Innovation Conference "Innovating in a Digital World", held in Copenhagen, Denmark on 05 June to 08 June 2022.
Event Proceedings: LUT Scientific and Expertise Publications: ISBN 978-952-335-694-8

Descriptive model for evolutionary innovation research in Product Generation Engineering

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Abstract: Industrial practice shows that products are developed in generations. Innovation success with complex technical systems can only be achieved economically by using existing solutions as references. The model of PGE – Product Generation Engineering describes product development based on variations and references. A literature review of evolutionary approaches in design research showed that existing approaches do not offer a holistic evolutionary view to support future demand- and context-driven product development. Especially the relations between changing context factors, reference-based variation activities, and innovation success are only partially investigated. This contribution presents a descriptive model for the evolution of mechatronic products based on the model of PGE, evolutionary models, and models for the context of product development. We applied and validated the descriptive model in two case studies (Toyota Hybrid Drive and Google Glass) and derived the first hypotheses for relations.

Keywords: Product development; Product Generation Engineering; Product Evolution; TRIZ; Innovation management; Case study; Design research

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1 Introduction

Industrial practice shows that products are developed in generations. Innovation success with complex technical systems can only be achieved economically and with manageable risk by using existing solutions as references. These references come from predecessors, competitors, and even industry-external products or concepts from research. The model of PGE – Product Generation Engineering describes these relationships. (Albers et al., 2019)

The product context of future product generations can be analyzed in strategic product planning using foresight methods (Gausemeier et al., 2019). In product development, the question arises as to which development activities on system level promise a high innovation potential in future product contexts. One approach to finding answers to this question is to take an evolutionary view of product development to learn from past successful and failed innovations. The core concept of this evolution analogy is that the development of new product generations and the struggle for successful innovation in their context can be understood as an evolutionary process in analogy to biology where systems interact with their context.

A literature review of existing evolutionary approaches in design research showed that the approaches support developers in solving technical problems but do not offer a holistic evolutionary view to support future demand- and context-driven product development. Especially the relations between changing context factors, reference-based variation activities, and innovation success are only partially investigated. An empirical, evolutionary view on product development based on the model of PGE offers potential for innovation research and the development of design support. (Pfaff et. al, 2022)

This contribution presents a descriptive model for research on the evolution of mechatronic products based on the model of PGE, evolutionary models, and descriptive models for the context of product development. We applied and validated the descriptive model in two case studies (Toyota Hybrid Drive and Google Glass) and derived the first hypotheses for relations.

2 State of the art

2.1 Innovation as a successful invention

Schumpeter (1934) defines innovation as an invention realized in a product and successfully established on the market (diffusion). Therefore, innovations can only be classified as such retrospectively. In product development, the term innovation potential can be used to describe the potential of a product to be successful in a future context.

To retrospectively classify a product as an innovation, or as a failed invention, various approaches exist (e.g. Bauer, 2006; Baccarini, 1999; Cooper & Kleinschmidt, 1987; Griffin & Page 1996). All classifications of a successful product include the economic success of the supplier. A supplier must achieve profit through a product to be successful. In addition to the supplier’s perspective, the sources mention satisfying the needs of customers or users as a criterion for success. According to Bauer (2006), a product can only be considered an innovation or a failed invention for a specific context.

Building on Schumpeter's understanding of innovation, Albers et al. (2018) propose three elements to be necessary for a successful innovation process: Product profile, invention, and market launch. The product profile models the demand situation and the intended customer, user, and supplier benefits of the product. The invention, consisting of idea and technical implementation, fulfils this product profile. The third necessary element for innovation success is a successful market launch.

Product developers have to design products for the constantly changing context of markets, society, law, politics, and the environment to enable progress and survive against competitors (Arthur, 2009). Product profiles and the boundary conditions, objectives and requirements for product development must be derived in this dynamic context. Process models such as the model of product design from VDI 2221 (2019) take this dynamic into account with the help of a model of context factors (Gericke et al., 2013; Hales & Gooch, 2004) that influence the product development activities.

2.2 PGE – Product Generation Engineering as a perspective on product development

The model of PGE - Product Generation Engineering according to Albers (2015) is a descriptive model for product development processes. The model of PGE is based on two fundamental hypotheses (see Figure 1). First, each new product generation G_n is developed based on references from existing or already planned sociotechnical systems and the associated documentation - also "new product developments" without a direct predecessor. These references and their interrelations are described as reference system elements (RSE) of the reference system R_n. Second, the subsystems of the G_n are developed by three types of variation: Carryover variation (CV), attribute variation (AV) and principle variation (PV). This description is possible on different system levels and in different system domains of mechatronic products, on function levels, and property levels. With CV, the corresponding RSE is carried over and is, if necessary, only adjusted at the interfaces during the system integration. AV is the new development of a subsystem while retaining the solution principle of the RSE and changing function-determining attributes or parameters. With PV, the function of the RSE is fulfilled by an alternative solution principle in the corresponding subsystem of the G_n. (Albers et al., 2019; Albers et al., 2020)

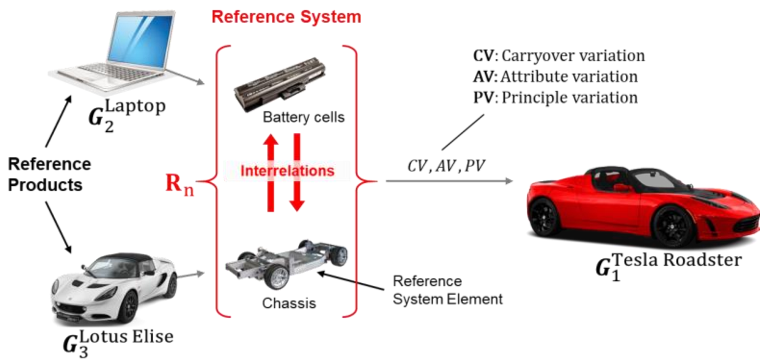

Figure 1 The reference system in the model of PGE (Albers et al., 2019). In the development of the Tesla roadster, the chassis of the Lotus Elise was carried over (CV). The battery cells from the reference product laptop were integrated with a new configuration (AV).

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The ratio of the number of subsystems developed by a particular variation type to the total number of subsystems of the new product generation gives the variation share of the three variation types δ_{CV}, δ_{AV} and δ_{PV} (Albers et al., 2015). Indicators for the identification of variation types are defined using the Contact-and-Channel-Approach (C&C²-A) (Albers et al., 2016).

The calculation of variation shares depends significantly on the system model considered. The number of subsystems analyzed (and thus the level of detail of the model) has a direct influence on the δ_{PV} detected: The more subsystems a system is divided into, the more often attribute or carryover variations are detected since microscopic observation tends to bring fewer principle variations with it. Vice versa it can be assumed that PV identified on the supersystem level is accompanied by AV and CV on the subsystem level (Rapp et al., 2020).

3 Research questions and research methodology

The core concept of the evolutionary view, to understand the development of systems in interaction with their context, together with the model of PGE offers potential for empirical research: the model of PGE describes the development of products as a mapping from reference system elements via variation operators to subsystems of the new product generation. Due to this high degree of formalization, the adaptable degree of abstraction on system levels, and the transferability to the mechatronic domains, the model of PGE enables the collection of data for the reference- and variation-based development of product generations. In a description model for evolutionary innovation research, the product context must be included. The aim of better understanding the evolution of mechatronic products in their context using the model of PGE led to the following research questions (RQ).

- RQ1: What elements and relations does a description model for the evolution of mechatronic products need for empirical research?
- RQ2: What relationships can be observed between changing context factors, reference-based variation activities (PGE), and innovation success?
- RQ3: How suitable is the descriptive model for the evolutionary description and the derivation of hypotheses for these relationships?

To answer RQ1, we synthesized a description model for the evolution of mechatronic products based on existing models from the design research. We validated the description model in two literature-based case studies of generations of mechatronic systems. We analyzed product generations, context and relationships of the successful innovation *Toyota Hybrid Drive* and the *Google Glass*, which is often classified as an unsuccessful invention. As a result, we generated and analyzed the first set of research data formalized with the description model for the evolution of mechatronic products.

The sources and their quality for the data on the product generations to analyze RSE, variation types and the influence of contextual factors varies. Besides scientific publications also manufacturers' operating manuals and marketing materials were used. In some cases, journalistic texts, teardowns, and technology reviews also served as sources. From the resulting research data, we inductively derived hypotheses for transferable relationships between PGE and context factors (RQ2) which need to be cross-validated with further case studies. In the discussion, we reflect on the application of the model and the research approach to answer RQ3.

4 Description model for the evolution of mechatronic products

The description model for the evolution of mechatronic products was synthesized based on the model of product context according to Gericke et al. (2013), the model of PGE (Albers et al., 2019), existing evolutionary approaches, especially evolution trees (Shpakovsky, 2006), and systems theory of technology (Ropohl, 2009). Figure 2 visualizes the model elements and their relations.

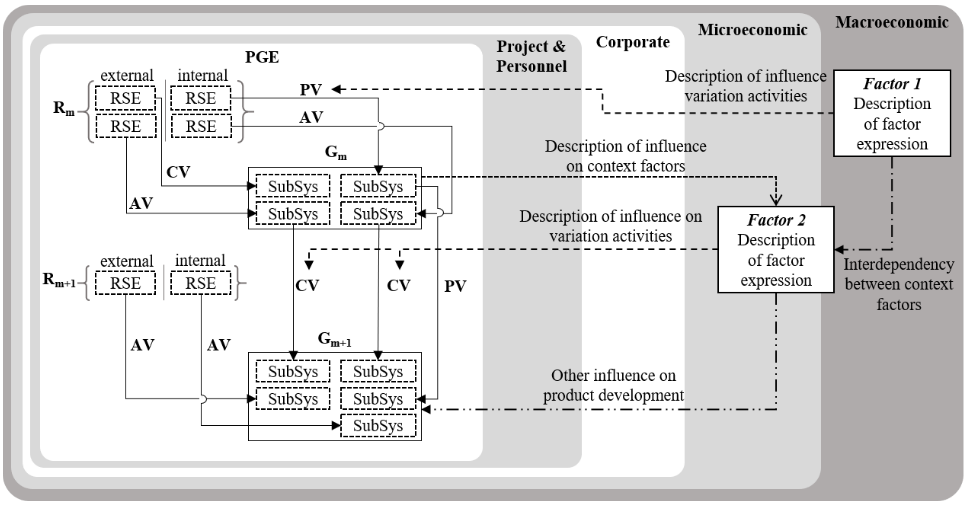

Figure 2 Visualization of the description model of the evolution of mechatronic products. PGE: Product Generation Engineering, CV: carryover variation, AV: attribute variation, PV: principle variation, G_m: Product Generation m, R_m: reference system which corresponds to G_m, RSE: reference system element, SubSys: subsystem.

The development of the product generations was described with the model of PGE and a hierarchical and structural system modelling of the R_m and G_m according to Ropohl (2009). The product context was modelled on the four levels macroeconomic, microeconomic, company, project and personnel according to Hales & Gooch (2004) to group the influencing factors. An extensive list of possible influencing factors within these levels can be found in Gericke et al. (2013). Each instance of a context factor in the model has an expression. The influence of expressed influencing factors on product development was modelled directly through the influence of factors on the type of variation in the sense of the model of PGE and indirectly by factors influencing other factors, which in turn influence variations.

The arrangement of the product generations from top to bottom results in a timeline from top to bottom, but this should be seen as qualitative in the visualization, even if dates are given. In addition to the succession of one product generation to the next, “branching” is also possible according to the concept of Shpakovsky’s evolution trees.

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These branches can lead to products within a company or competitors and partners in the microeconomic environment (see Figure 6).

5 Results of the application of the description model in two case studies

In the following two case studies, the product development and the development of the product context are described, formalized and visualized with the description model. For this purpose, the development of the variation shares δ_{CV}, δ_{AV} and δ_{PV} over the product generations is analyzed and visualized.

5.1 Toyota Hybrid System Gearbox (THS-G)

The $G_1^{THS\text{-}G}$ was introduced in the first generation of the Toyota Prius launched in 1997. It was a power-split hybrid drive which combines a combustion engine with two electrical machines (EM1 and EM2). The power of the combustion engine, EM1, and EM2 is combined in the gearbox so that the hybrid drive realized different driving modes. (Hofmann, 2014) The hybrid gearboxes of the Prius from 1997 to 2016 were the systems under investigation in this case study. For the analysis, the gearbox was modelled with three subsystems: The power-split with planetary gearset and EM1, the connection of EM2 and the transmission to the differential (see Figure 3).

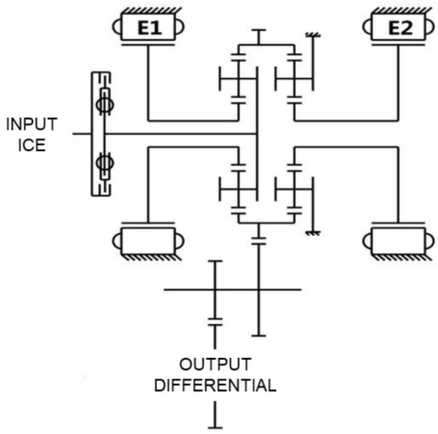

Figure 3 Principle sketch of $G_4^{THS\text{-}G}$ (Xu et al., 2018). Characteristic for the first four generations is the coaxial layout of both electrical machines (E1 and E2)

5.1.1 Analysis of the first THS-G generation

The development of new, low-emission drive systems in the 1990s was driven in particular by legislation (Tomlins et al. 2021): In the 1992 Earth Charter, vehicle manufacturers declared a common goal of producing vehicles with the lowest possible emissions (Nonaka & Peltokorpi 2006, p. 93). The strictest legal framework regarding emissions for the automotive industry and an incentive program for vehicle electrification (ZEV - Zero-Emission Vehicle program) was created in 1990 in California. This was considered the basis and orientation for the development of hybrid electric vehicles (HEVs) (Hofmann 2014, p. 57). The obligation to sell a certain proportion of purely electric or fuel cell vehicles by 1998 forced manufacturers to develop electrified drive systems (McConnell et al. 2019, p. 3).

These political and legal developments shaped Toyota's corporate strategy: their goal became the development of a highly efficient vehicle for the 21st century. To achieve this goal, all necessary financial and human resources were allocated to the G_1^{THS-G} project. (Nonaka and Peltokorpi 2006, pp. 96-98)

RSEs for the development of the first hybrid powertrain were previous projects on serial hybrids. The earliest project in this regard began in 1965 and produced two prototypes in 1975 and 1977, which used a gas turbine to power a battery and an electric motor (Toyota Motor Corporation 2017). Even before the Prius, Toyota put a serial full hybrid minibus into production in 1997 with the Coaster Hybrid EV (Toyota Motor Corporation 1997).

The project and personnel level were particularly important for the development of the G_1^{THS-G}: At an early stage of the project, clear efficiency targets were set for the new drive. Fuel efficiency was to be increased by 100% compared to a comparable Toyota Corolla with automatic transmission (Nonaka and Peltokorpi 2006, pp. 96-98). To meet these goals, the hierarchical structure was broken up and core team management was installed, and the locations of the development teams were also merged locally. (Tomlins et al. 2021). To meet the tight schedule of the project, research and development took place in close consultation among the departments. (Nonaka and Peltokorpi 2006, pp. 96-98).

A microeconomic influencing factor was that the charging infrastructure for batteries was not sufficiently developed. It was decided to develop a self-charging concept in which the internal combustion engine would charge the battery while driving.

The Kyoto Conference in 1997 prompted Toyota's plans to bring hybrids to market as early as possible. Therefore, they wanted to enter the market in the same year as the Kyoto Protocol to ensure a correspondingly large impact on the automotive industry (Nonaka and Peltokorpi 2006, pp. 96-98). Figure 4 summarizes the influences of context factors on the development of G_1^{THS-G}.

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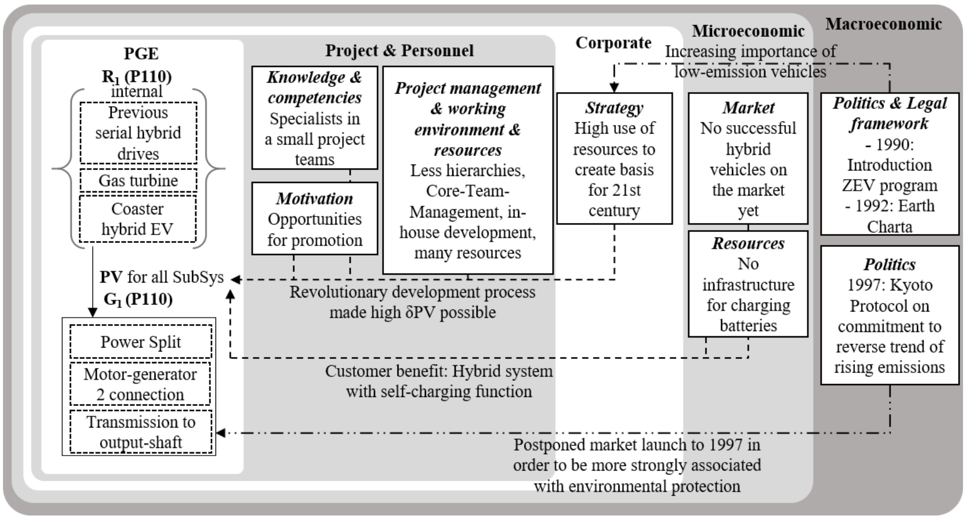

Figure 4 Influences of context factors on the development of $G_1^{THS\text{-}G}$. The analysis shows that the macroeconomic and microeconomic context have generated high innovation pressure in the direction of electrified powertrains. Toyota had many internal references available for development, but at the system level studied, principle variations still had to be made for all subsystems. The success of the development was enabled by corporate strategy and the internal development context.

5.1.2 Analysis of the transition from coaxial to parallel layout

Under increasing competitive pressure and further success the $G_2^{THS\text{-}G}$, $G_3^{THS\text{-}G}$ and $G_4^{THS\text{-}G}$ are developed. In these product generations, the principle is maintained and improved which resulted in AV and CV at the system level under investigation (see Figure 7). After the $G_3^{THS\text{-}G}$, the development of further hybrid transmissions for other vehicle segments of Toyota results in new parallel product lines and branches in the evolution model. These are not described in further detail in this case study. The $G_5^{THS\text{-}G}$ marked a change from the coaxial layout of the two electrical machines to a parallel layout. This layout was adapted from a gearbox, known as the HD-10, developed for Ford by Toyota’s supplier Aisin. In both gearboxes, EM2 is located on a parallel shaft to the power-split planetary gearset and EM1 and is connected to the intermediate shaft of the output to the differential via gears (see Figure 5). (Nonaka & Peltokorpi, 2006; Hofmann, 2014; Tomlins et al. 2021)

The Aisin HD-10 was used as an RSE for the development of the connection of EM2 and the transmission to the differential in $G_5^{THS\text{-}G}$. This resulted in a lower risk AV for Toyota instead of a PV. This was possible because of Toyota’s open innovation strategy. Ford licensed hybrid drive patents from Toyota, but also applied itself for more than 100 patents (Toyota-Media 2004). Toyota established close relationships with some of its suppliers and participated in them both financially and in project management, but also in defining strategies. Toyota often holds more than 20% of the shares in these suppliers (Müller 2009, pp. 17-20).

Principle sketch $G_5^{THS\text{-}G}$ (P610) Principle sketch Aisin HD-10

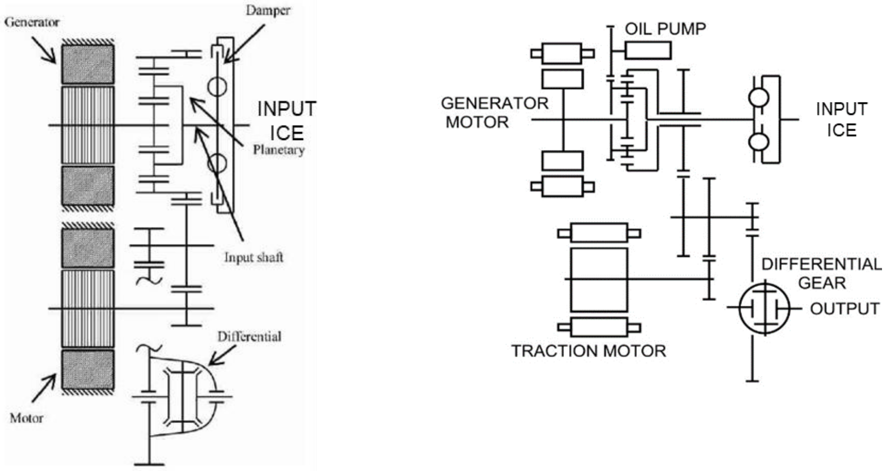

Figure 5 Comparison of principle sketches of the $G_5^{THS\text{-}G}$ (P610) (Taniguchi et al. 2016) and Aisin HD-10 (Hisada et al. 2005).

With the $G_6^{THS\text{-}G}$, Toyota acted in anticipation of an announced change in the legal framework of California. Since 2018, a minimum percentage of total vehicle sales must consist of all-electric vehicles and plug-in hybrids. Since regular transmissions did not meet these requirements, Toyota decided to develop a plug-in hybrid based on the $G_5^{THS\text{-}G}$, the $G_6^{THS\text{-}G}$ (McConnell et al. 2019, pp. 10-12).

To save costs, the $G_6^{THS\text{-}G}$ was developed with as many CV and AV with RSE from the $G_5^{THS\text{-}G}$ as possible. To be able to use both electrical machines during electric driving, a new subsystem was added in the form of a freewheel clutch which resulted in a PV for the power-split. (Suzuki et al. 2017)

Figure 6 summarizes the influences of context factors on the development of the $G_5^{THS\text{-}G}$ and the $G_6^{THS\text{-}G}$.

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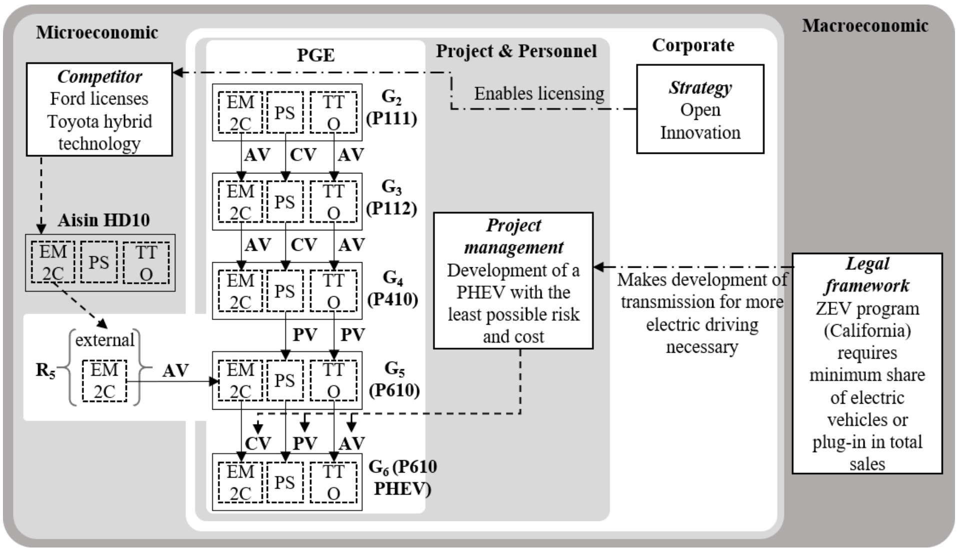

Figure 6 Influences of context factors on the development of $G_5^{THS\text{-}G}$ and the $G_6^{THS\text{-}G}$. PS: power-split with planetary gearset and EM1, EM2C: connection of EM2, TTO: transmission to the differential. The branching out after $G_3^{THS\text{-}G}$ into the other segments is not shown. The previous partial licensing to Ford allowed Toyota to access the Aisin HD10 as an external RSE for the $G_5^{THS\text{-}G}$ to meet cost and risk targets.

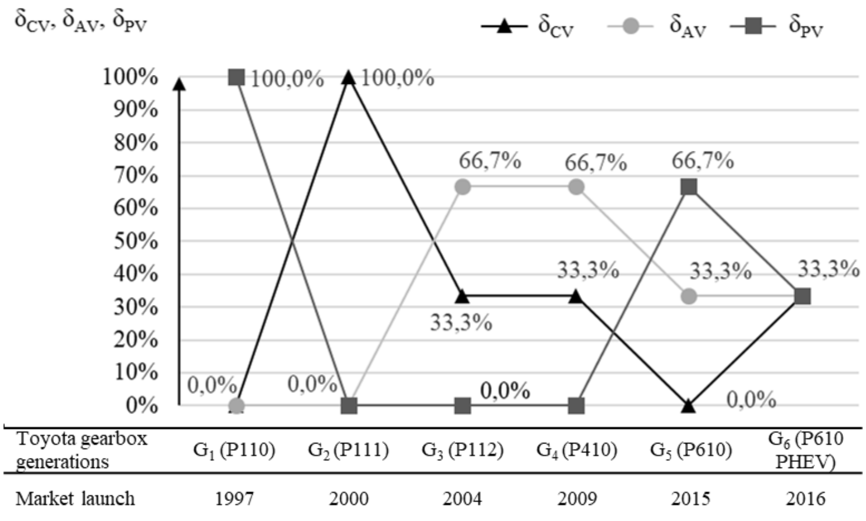

Figure 7 Variation shares δ_{CV}, δ_{AV} and δ_{PV} over the six investigated Toyota hybrid system gearbox generations. $G_1^{THS\text{-}G}$ and $G_5^{THS\text{-}G}$ stand out with high δ_{PV}.

5.2 Google-Glass

The Google Glass is an AR - Augmented Reality glasses of the company Google. It was introduced to the commercial business-to-customer (B2C) market in 2014 and is currently in its fourth generation (see Figure 8 to Figure 11). Google Glass was not used by the broad population but is now sold in the professional business-to-business (B2B) market. $G_1^{\text{Google Glass}}$ and $G_2^{\text{Google Glass}}$ can be classified as a failed invention in the B2C market. For the analysis, the Google Glass was modelled with eight subsystems: Frame, display, camera, touch-UI, computing unit and operating system, port, battery, speakers.

Figure 8 $G_1^{\text{Google Glass}}$ (Explorer Edition) (Cooper Hewitt – Design Museum, 2017)

Figure 9 $G_2^{\text{Google Glass}}$ (Explorer Edition 2) (PCMag Australia, 2014)

Figure 10 $G_3^{\text{Google Glass}}$ (Enterprise Edition) (Matta, 2017)

Figure 11 $G_4^{\text{Google Glass}}$ (Enterprise Edition 2) (Google, 2019)

5.2.1 Analysis of the product generations and the product context

Google created a new product category in the technology market with the $G_1^{\text{Google Glass}}$ (Fischer, 2018). The $G_1^{\text{Google Glass}}$ (Figure 8) was launched in 2014 in the US and had a 570 mAh battery, a camera with a five-megapixel resolution, a 640 x 360-pixel display, one gigabyte of RAM, and 16 gigabytes of storage. The $G_1^{\text{Google Glass}}$ could be operated via a touchpad, which reacted to various gestures. It had a micro-USB port and speakers based on the bone conduction principle. PV occurred in the display and the computing subsystem consisting of the computing unit and operating system. The remaining subsystems were developed based on internal and external RSE with CV and AV (see Figure 13). (Google 2014, Torborg & Simpson, Tiefenthäler 2013)

To potential customers, it was unclear for which problem the product was supposed to offer a solution (Reynolds, 2015). The unknown purpose meant that Google Glass was mainly used by technology enthusiasts rather than the intended mass population (Kuhn & Bernau, 2014).

The $G_1^{\text{Google Glass}}$ met with worldwide criticism even before it reached market maturity, which can be described through the influence of macroeconomic factors. Data protectionists criticized the possibility of filming other people with the glasses without them noticing. There was also criticism that the user's recordings could be transferred to the company's servers for evaluation or even handed over to government agencies. A citizens' initiative called "Stop The Cyborgs," founded in response to the Google Glass project, dedicated itself to opposition to the data glasses. The advocacy group pursued the goal of convincing tradespeople in the U.S. to ban Google Glass from their premises. Bans on Google Glass wearers in some bars, restaurants, nightclubs, and movie theatres were consequences of the campaign. (Beuth, 2013; Beuth, 2014, Clauß, 2015) The

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Google Glass was even banned in Russia and Ukraine, according to media reports, because they could have been used for spionage purposes (Fischer, 2018).

The $G_2^{Google\ Glass}$ (Figure 9) was released a short time later in 2015. A PV of the frame made it possible to use prescription lenses. In addition, the RAM was increased from one to two gigabytes. The other subsystems were developed with minor adjustments classified as CV (see Figure 13). In response to the changing macroeconomic legal and social context, no adjustments were made to the product in the 2nd generation.

Other providers such as Microsoft, meta and magic leap presented their AR glasses in 2016 - 2018 with a focus on the B2B market. Increasing competition and a lack of acceptance among the wider population forced Google to change its strategy and the product profile of Google Glass. (Fischer, 2018)

The $G_3^{Google\ Glass}$ (Figure 10) was launched in 2017 and brought new features under the name “Enterprise Edition” to fit the new targeted professionals and the B2B market. The OMAP processor was replaced by an Intel Atom processor and the storage space was increased from 16 to 32 gigabytes. In addition, the battery was enlarged. The bone conduction speakers used in the $G_2^{Google\ Glass}$ were replaced with dynamic speakers. The micro-USB port used in the first two generations was changed to a pin-based charging system. $G_3^{Google\ Glass}$ was equipped with GPS and a barometer. (Hall, 2017) For the development of the $G_3^{Google\ Glass}$, external RSE were used to develop the computing unit, the USB port and the speakers. These subsystems were also influenced by external RSE in the $G_4^{Google\ Glass}$.

In the $G_4^{Google\ Glass}$ (Figure 12) launched in 2019, the Intel Atom processor was replaced by a Qualcomm Snapdragon processor and three gigabytes of RAM. It was equipped with an eight-megapixel camera and the pin-based charging system was changed for a USB Type-C port. $G_4^{Google\ Glass}$ was also waterproof and dust-resistant. (Google, 2019)

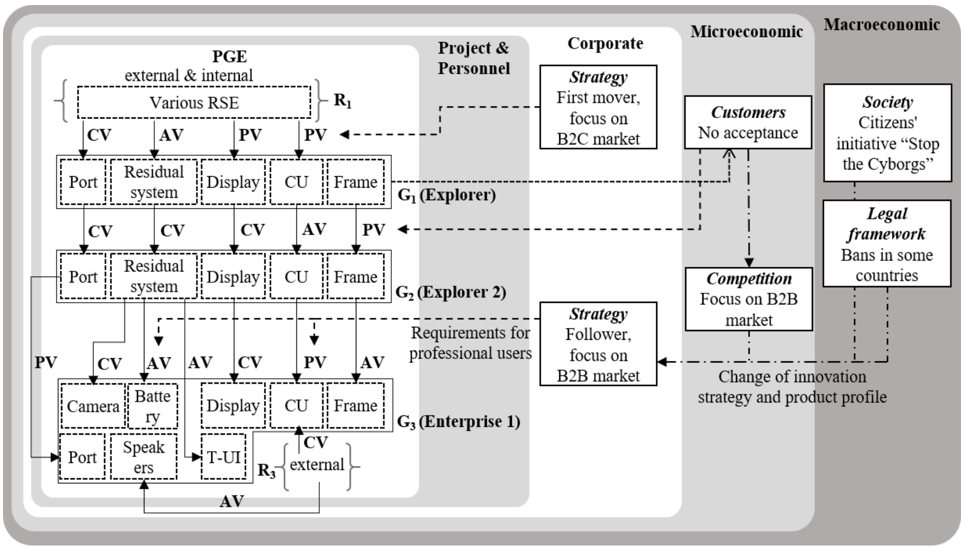

Figure 13 Influences of context factors on the development of $G_1^{Google\ Glass}$, $G_2^{Google\ Glass}$ and $G_3^{Google\ Glass}$. CU: computing unit and operating system, T-UI: touch UI. $G_4^{Google\ Glass}$ is not visualized due to a lack of knowledge on interactions with the product context. The model showed that the changing macroeconomic context was not responded to in the $G_2^{Google\ Glass}$ but in the $G_3^{Google\ Glass}$ by changing the strategy and product profile.

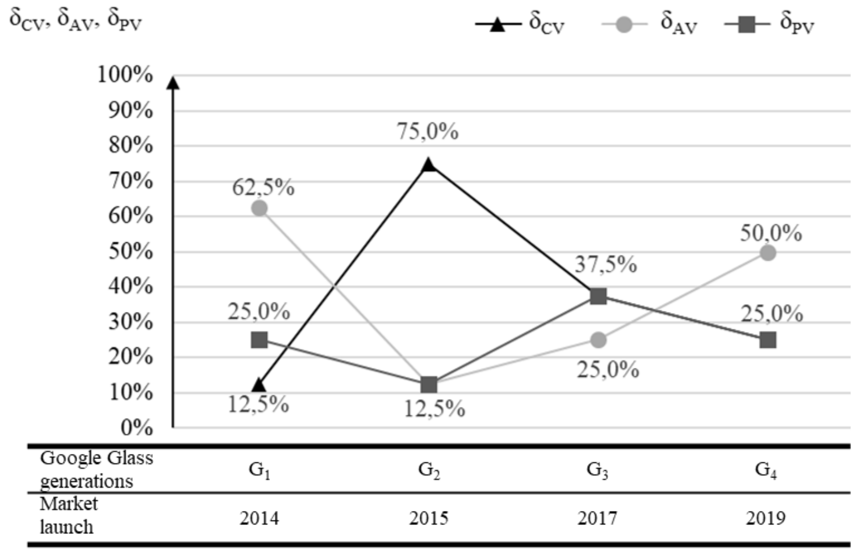

Figure 14 Variation shares δ_{CV}, δ_{AV} and δ_{PV} over the four Google Glass generations. In the development of the second product generation, Google retained the concept and only varied the frame (PV) and computing unit (AV). While the first two generations hardly differ, major changes can be seen in the leap from the $G_2^{\text{Google Glass}}$ to the $G_3^{\text{Google Glass}}$.

5 Discussion

With the description model in section 3, we answered RQ1 *What elements and relations does a description model for the evolution of mechatronic products need for empirical research?* with a new description model based on existing description models from the state of research. The combination of the model of PGE, evolutionary models, and descriptive models for the context of product development allowed the evolutionary description of two case studies. We use the term “evolutionary” because the description model integrates the core concepts of the evolution analogy (Pfaff et al., 2022): the reference and variation based development of new (product) generations under the influence of the context and the struggle for success (innovation) in their context.

To discuss RQ2 *What relationships can be observed between changing context factors, reference-based variation activities (PGE), and innovation success?* we summarized the hypotheses derived in the two case studies for changing context factors, reference-based variation activities (PGE), and innovation success. The product generations that were the basis for the hypotheses are referenced in brackets.

- The early and continuous monitoring of the macroeconomic environment is particularly relevant for innovation success. CV and AV of subsystems are not sufficient in the long term to deal with more progressive legal frameworks and changing social conditions. PV in subsystems or changes in the product profile are necessary. ($G_2^{\text{Google Glass}}$, $G_3^{\text{Google Glass}}$, $G_6^{\text{THS-G}}$)

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- Successful product generations with many new or improved customer-relevant product properties use external RSE to keep the overall δ_{PV} low ($G_1^{THS\text{-}G}$, $G_5^{THS\text{-}G}$, $G_3^{Google\ Glass}$).
- The successful development of a product generation with a high δ_{PV} is supported by a special internal context such as core team management, motivational structures for staff and resources ($G_1^{THS\text{-}G}$).
- Open innovation strategies result in parallel development paths or branches which can again provide valuable RSE resulting in a lower δ_{PV} which leads to decreasing cost and risk ($G_5^{THS\text{-}G}$)
- Product generations without predecessors do not need to have a high δ_{AV} and δ_{PV} to assess new markets ($G_1^{Google\ Glass}$)

Considering RQ3 *How suitable is the descriptive model for the evolutionary description and the derivation of hypotheses for these relationships?* the first set of hypotheses indicated that the description model fulfilled its purpose and proved applicable in the analysis of the product generations and their context. For the generation of further insights, more data and advanced analysis and visualization methods would be beneficial.

6 Outlook

We are currently collecting and conducting literature-based, interview-based and participating case studies to derive further hypotheses and verify/falsify derived hypotheses through cross-validation.

The empirical data and theoretical description of the relationships between context factors, product development activities in terms of PGE and innovation success (retrospective) to assess innovation potential (prospective) has potential for innovation research. To gain deeper insights into the relationship between engineering on the system-level and innovation success, we are currently conducting further case studies and developing a digitalized version of the model which shall enable further analysis methods and be made available to the research community.

The validated theoretical findings of this and further descriptive studies need to be made applicable to development practice. The application of the knowledge through applicable and useful design support and the validation of the impact on innovation success in real design processes is a further research objective.

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