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Insights into System Evolution from a Cross-Case Analysis Using the Model of SGE - System Generation Engineering

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Abstract

Product planning and development in companies must become more efficient while maintaining or increasing the ability to innovate. The use of data from previous products and other references offers significant potential for increasing efficiency. One approach to data-driven engineering is SGE - System Generation Engineering. SGE involves utilizing suitable internal and external references to develop subsystems with carryover variation where possible to reduce costs and risks. To leverage innovation potential new development through attribute and principle variation is applied where necessary. Cross-generational SGE modeling combined with contextual and market success data generates data sets that describe how system generations evolve. With an evolutionary perspective on product engineering and innovation, this study established a research dataset with 14 literature-based, retrospective case studies on the evolution of technical systems and derived insights into the evolution of products from a cross-case analysis to support product engineering through heuristics and evolution patterns.

Keywords
Product Development, Product Management, Engineering Management, Innovation and Case Studies.

1. Introduction
Product planning and development in companies must become more efficient while maintaining or increasing their ability to innovate (Isaksson et al. 2019, Schoemaker et al. 2018). In the development of new product generations, the use of data from previous generations and other references offers significant potential for increasing efficiency (Lachmayer and Mozgova 2022). One approach to operationalize data-driven engineering is SGE - System Generation Engineering (Albers and Rapp 2022). SGE models product development as mapping references to the subsystems of the system in development by carryover, attribute, and principle variation (CV, AV, PV). References are elements of the reference system and come from predecessors, competitors, and even industry-external products or concepts from research (Albers and Rapp 2022). A promising strategy is to use CV based on internal references where possible to reduce cost and risk and to use AV, PV, and external references where necessary to leverage innovation potential. Cross-generational SGE modeling combined with contextual and market success data generates data sets that describe how system generations evolve. A fundamental mechanism of biological evolution and innovation is the "Survival of the fittest": The system that best adapts to a constantly changing context is successful (Arthur 2009). The analysis of SGE, context, and market success data can provide insights into the evolution of systems, aiding strategic product planning and development in making variation decisions with high potential for market success (Pfaff et al. 2022).

1.1 Objectives
The analysis of SGE, context, and market success data has not yet been systematically applied to a dataset with multiple case studies. Similarly, no attempt has been made to derive generalizable insights into the evolution of products from such data. Therefore, this study pursues the following objectives:

1) establish a research dataset with multiple case studies on the evolution of technical systems based on the model of SGE
2) derive insights into the evolution of products from a cross-case analysis
3) support product planning and development in the creation of new product generations with these insights

The first and second objectives are the focus of this publication. The third objective is pursued within the scope of this publication, but its achievement is not evaluated and must be addressed in subsequent studies.

2. Literature Review

The first part of the literature review encompasses the underlying understanding of innovation in this study, with a focus on product innovation from an engineering perspective, as well as existing approaches in product planning and product development that build on the analogy of evolution. The second part explains the fundamentals of the model of SGE – System Generation Engineering.

2.1 Innovation and Evolution from a Product Engineering Point of View

Product engineering is part of the product lifecycle and describes the fundamental process from the product or business idea to the start of series production. It encompasses the three main areas of strategic product planning, product development, and production system development (VDI 2019). Isaakson at al. (2019) concluded in their literature review that the current understanding of "innovation" from a product engineering point of view focuses on novelty. Schumpeter (1934) defines innovation as an invention realized in a product and successfully established on the market. Following Schumpeter's definition, market success is a necessary condition and innovations can only be classified as such retrospectively and for a specific context. Various approaches exist to classify a product as a failed invention or an innovation (e.g. Bauer 2006, Baccarini 1999, Griffin and Page 1996, Cooper and Kleinschmidt 1987). All classification approaches include the economic success of the product as a necessary criterion.

Retrospective case studies satisfy this definition of innovation and offer the potential to understand the mechanisms of product evolution (Bauer 2006). It is important to consider the product context and customer needs for innovation (Chong and Chen 2010, Cooper & Kleinschmidt 1987). In product engineering, the external macroeconomic and microeconomic context, as well as the internal company product context, are often described based on context factors (Gericke et al. 2013, Hales and Gooch 2004). Albers et al. (2018) propose product profiles to model the intended customer, user, and provider benefits of the product in a solution-open way, which can also be used for retrospective case studies. The context of product development is VUCA: volatile, uncertain, complex, and ambiguous (Schoemaker et al. 2018). In this constantly changing context of society, markets, politics, law, and the environment, organizations have to plan and develop products which enable progress and "survive" against competitors (Arthur 2009).

This analogy to the "survival of the fittest" in biological evolution motivated evolutionary approaches in design research. These approaches developed design principles and laws (Klein 2014, Zlotin and Zusman 2013) based on Altschuller, "the father of TRIZ" (1986), data-driven methodological approaches (e.g. Biswas et al. 2021, Lachmayer and Mozgova 2022, Li et al. 2022) and theories (e.g. Vajna et al. 2011).
Another analogy that these evolutionary approaches use is building on parent generations to create inventions. This analogy is particularly useful, as all systems are developed based on references and the share of new developments for mechatronic systems in most projects is less than 20% (Albers et al. 2022, Knieke et al. 2022, Kirchner and Neudörfer 2021). In addition to evolutionary approaches, many others support the reuse of knowledge and artefacts from previous design processes, such as design reuse, engineering changes, the C-K theory (Alblas and Jayaram 2015, Hatchuel and Weil 2003) and SGE – System Generation Engineering (Albers et al. 2022).

2.2 SGE - System Generation Engineering

The model of SGE - System Generation Engineering according to Albers (2022) reflects the evolutionary analogy (Figure 1) by describing product development based on references and in generations (Pfaff et al. 2022). The system generation in development with the next market entry is labelled with the index i=n ($G_{i=n}$). The relevant references for the development of the $G_{i=n}$ are structured in the reference system ($R_{i=n}$) as reference system elements (RSE) and come from predecessors (e.g. $G_{i=n-1}$), competitors, and industry-external products or from research. Another analogy to evolution which other models do not address is operators which describe the creation of new generations based on references (analogous to recombination and mutation in genetics). SGE describes product development as the mapping of RSE to the subsystems of the system in development ($G_{i=n}$) by carryover-, attribute-, and principle variation (Albers et al. 2022):

- **Carryover Variation (CV)**: *"a RSE is carried over into the new system generation, whereby the interior of this element is regarded as a "black box" and adjustments are made according to the requirements of system integration and boundary conditions at the interfaces."*
- **Attribute Variation (AV)**: *"the link of RSE is maintained in the new system generation. The solution principle remains unchanged compared to the reference system. The attribute(s) of the RSE are varied."*
- **Principle Variation (PV)**: *"RSE and their linkage are varied such that elements and links are removed or added. Thus, a new solution principle is realised, which is new in comparison to the reference system."*

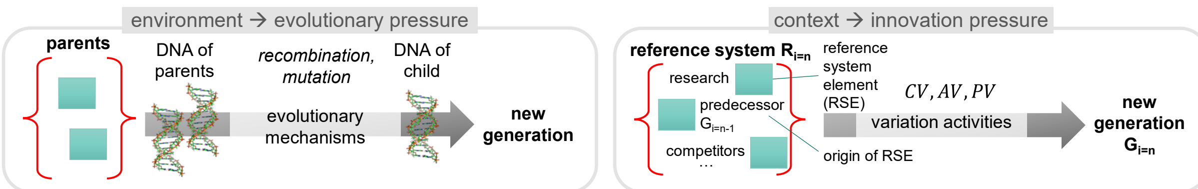

Figure 1. Conceptual comparison of product development and synthetic theory of evolution

The ratio of the number of subsystems developed by a variation type to the total number of subsystems of the new system generation gives the variation share of the three variation types δCV, δAV, and δPV. The sum of δAV and δPV is also referred to as new development share δND (Albers and Rapp 2022).
The model of SGE can be applied from a prescriptive and a retrospective perspective (Albers and Rapp 2022). Prescriptively, the intended variations for individual subsystems based on RSE serve as planning assumptions and specifications of the design space. Retrospectively, it enables formalized data collection in product development processes and thus data-driven approaches for design support. Variations are analyzed by comparing the subsystems of a developed system with the underlying RSE. The retrospective calculation of variation shares is influenced by the chosen system model and the underlying RSE and can be inaccurate (Rapp et al. 2020).

3. Methods

Building on the objectives, the understanding of innovation, the analogy of evolution, and the fundamentals of SGE, a central research question was formulated: *What relationships exist between context factors, reference-based variation activities (SGE), and market success?* This research question supports the achievement of objectives 1) and 2). To achieve objective 3), the insights should be formulated as situational heuristics that trigger actions and patterns that describe the evolution of systems.

Case studies and a cross-case analysis of 14 systems were encompassed in our research methodology. The data for the 14 case studies were collected through literature reviews. According to Yin (2018), these individual studies cannot be considered case studies, as empirical methods are a prerequisite. Woodside and Wilson (2003) describe case studies as *"inquiry focusing on describing, understanding, predicting, and/or controlling the individual"*. We refer to the individual cases as "case studies" with the limitation of literature-based data collection. In our study, an individual case is the evolution of one technical system over system generations. The case studies were conducted in Bachelor- and Master-theses by students supervised by the authors of this paper. Each case study involved five steps (Table 1).

The cross-case analysis was qualitative, partly case-based and iterative according to Grounded Theory (Corbin and Strauss 1990), and partly variable-based according to Cash (Cash 2018). In the iterative analysis, the heuristics (5.3 and 5.4) and evolution patterns (5.5) emerging from the currently analyzed case study were compared with other case studies. In the variable-based analysis, the case studies were collectively compared and examined. An example of this is the comparison of variation shares in Chapter 5.2.

Table 1: Research approach for the case studies

<table>
<tr><th>Step</th><th colspan="3">Description of research method</th></tr>
<tr><td>1</td><td colspan="3">Selecting the system generations and variants under investigation for the chosen system (see table 2)</td></tr>
<tr><td>2</td><td colspan="3">Building an initial system model to describe the development across system generations (see table 2, "subsystems"). An appropriate level of detail had to be ensured.</td></tr>
<tr><td>3</td><td colspan="3">Technical analysis (SGE), product profile analysis, and context analysis: The information was mostly collected through literature analysis. The literature consisted of scientific publications, grey literature (e.g. marketing material, annual reports) and internet documents (e.g. teardowns, reviews). The sources are listed directly in the data set under the respective system generations.</td></tr>
<tr><td></td><td>Technical (SGE): RSE and variation types were determined for the system generations. In most cases, the previous generation was the dominant origin for RSE.</td><td>Product profile: limited to claim (main product goal) and the provider and user/customer benefits. Results were the product profile variations.</td><td>Context: Goal were key factors that affected SGE. The results were factors and expressions for each system generation under investigation. The analysis was carried out with partially open coding in the factor categories Micro-, Macroeconomic and Company, according to (Gericke et al. 2013). A detailed context analysis has not been done for all case studies (Table 2).</td></tr>
<tr><td>4</td><td colspan="3">Evaluating market success: Metric depending on the product and the available data.</td></tr>
<tr><td>5</td><td colspan="3">Summarizing the results in the dataset and a visualization (example in Figure 4).</td></tr>
</table>

4. Data Collection

The case studies were broad: Automotive subsystems, household electronics, consumer electronics, and spacecraft (Table 2). The hypothesis underlying the breadth of the data set is the cross-industry and cross-domain applicability of the model of SGE. The resulting data set is published and continuously updated at https://doi.org/10.5281/zenodo.14628595. The dataset currently consists of 118 system generations and product profiles, 1180 variation relationships and RSEs, and 321 contextual factors. The scope of the data set is too broad and the number of data points is too low for a quantitative analysis.

Table 2: Overview over the case studies.

Nr.	**Case study** Provider: Product	**Product type** B2C: Business-to-Consumer B2B: Business-to-Business	**Gener-ations** (variants)	**Sub-sys-tems**	**Success metrics** quan(titative) qual(itative)	**Context Analysis**
1	Apple: iPhone	Smartphone, B2C	17 (26)	11	quan., sold units	detailed
2	Xiaomi: Mi Ultra	Smartphone, B2C	5	11	quan., sold units	initial
3	Toyota: Hybrid gearbox (THS-G)	Automotive Gearbox, B2C	6 (20)	3	qualitative	detailed
4	VW: Dual clutch transmission (VW DCT)	Automotive Gearbox, B2C	6	25-28	qualitative	detailed
5	Google: Glass	Wearable, B2C, B2C	4	8	qualitative	detailed
6	Vorwerk: Thermomix	Kitchen Appliance, B2C	8	6-9	partly quan., sold units/partly qual.	detailed
7	Sony: PlayStation	Game Console, B2C	5	9	quan., sold units	detailed
8	BYD: Traction Battery	Traction Battery, B2C	6	4	quan., sold units	detailed
9	Ultimate Ears: BOOM	Bluetooth Speaker, B2C	3 (8)	9	qualitative	initial
10	SEW Eurodrive: DTS (SEW DTS)	Driverless transport system (DTS), B2B	14	16-23	qualitative	none
11	SpaceX: Falcon	Spacecraft, B2B	5	9	quan., launches	initial
12	Ariane Group: Ariane	Spacecraft, B2B	3(6)	8	quan., launches	initial
13	iRobot: Roomba	Vacuum robot, B2C	3	11	qualitative	none
14	Dreame: Vacuum robot	Vacuum robot, B2C	3	11	qualitative	none

The data collection in the case studies was based on an Entity-Relationship data model (Chen 1976) with three entities, each of which was mapped in a table with n entries (Figure 2). The data structure with few, attribute-rich entities resulted from the iterative development of the data model during the study and its implementation in Microsoft Excel, for which a low number of tables was advantageous. Table I lists all system generations examined in the case studies and data on product profiles, success, and sources relevant to the system generation. Table II includes the variations of the subsystems with RSE. For each system generation in Table I, N variations from Table II were assigned, where N corresponds to the number of modelled subsystems (see Vorwerk Thermomix example in 5.1). Each entry in Table III corresponds to a context factor relevant to the development of a system generation in Table 1.

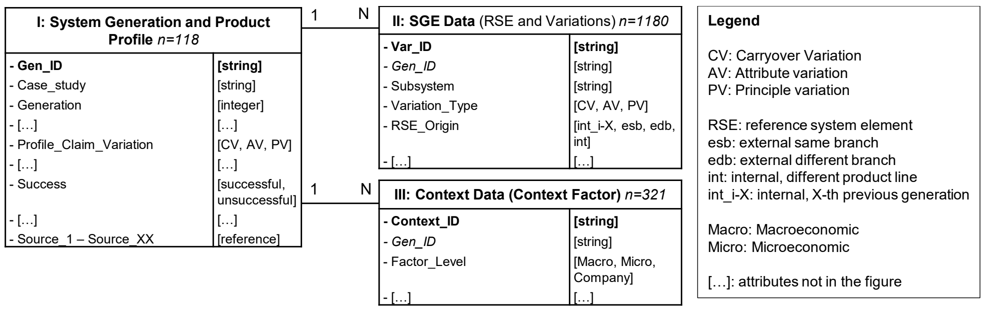

Figure 2. Entity-relationship data model for the dataset.

Figure 3 (left) shows the distribution of variation types across all 1180 evaluated variation activities. δND, especially δPV, appears to be over-represented compared to previous studies (Albers et al. 2015, Kirchner and Neudörfer 2021, Knieke et al. 2022). There is an imbalance between the individual studies due to the different levels of detail, number of generations, and variation relationships per study. The Apple iPhone, SEW DTS and VW DCT studies account for over 50% of the variation data points. Figure 3 (middle) shows the distribution of the origin of the RSE on which the variations are based. The proportion of external references could be higher in reality but these are very difficult to identify using literature-based methods. Figure 3 (right) displays that the data set contains only 5% unsuccessful system generations which introduces the risk of a "survivor bias". This overrepresentation of successful generations is difficult to eliminate, as more success stories are published than failures. From the "indifferent" generations, two are counted as successful as they were more successful than their predecessor $G_{i=n-1}$ and ten as unsuccessful as they were less successful.

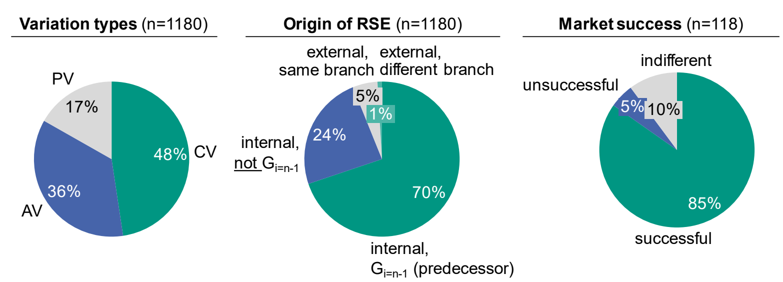

Figure 3. Variation types (c.f. section 2.2; CV: carryover variation, AV: attribute variation, PV: principle variation), Origin of reference system elements (RSE), and market success in the dataset.

5. Results and Discussion

This section begins with the example of the Vorwerk Thermomix case study in 5.1. Section 5.1 aims to provide an exemplary, detailed view of the case study approach and the collected data. The results of the other case studies can be found in the dataset. In section 5.2, the system evolution of the 14 case studies is presented and compared on a highly condensed, overarching level to gain an overall impression. Sections 5.2, 5.3, and 5.4 present the results of the in-depth cross-case analysis. Section 5.5 concludes with a discussion of the validity of the dataset and the findings.

5.1 Example Case Study: Vorwerk Thermomix

In the Thermomix case study, the eight system generations that were introduced from 1971 to 2019 were examined. Figure 4 presents an excerpt of the central evolution visualization created for each case study. The visualization in the "SGE" column provides an overview of how the product profile and subsystems have evolved over generations and from which sources the RSE were incorporated into the reference system. For products with multiple examined variants (case studies 1, 3, 4, and 9), this section illustrates the portfolio development with the "inheritance" of RSE across variants. In the center ("Context"), the context factors are listed at the macroeconomic, microeconomic, and company levels, along with their dimensions and expressions (high/low). The data on market success - depending on the published figures, in some studies only qualitatively (c.f. Table 2) - are shown on the right-hand side.

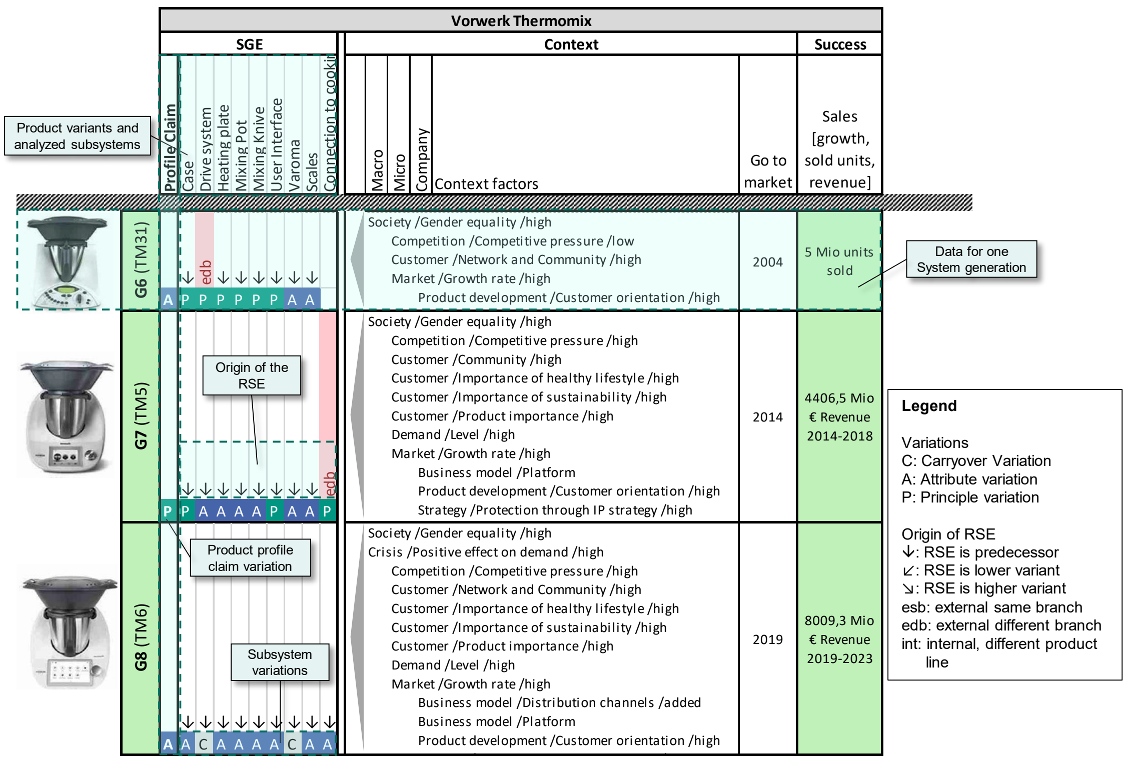

Figure 4. Excerpt from the visualization of the Vorwerk: Thermomix case study.

5.2 Comparison of System Evolutions

The histograms in Figure 5 show the distribution of variation shares for the system generations investigated. δAV and δCV show a bell curve character with pronounced very high shares. Half of the generations examined have a PV share δPV of 0-10%. δND is relatively evenly distributed and there are over 20 system generations with a very high δND over 90%. These tendencies should not yet be over-interpreted due to the non-quantitative analysis.

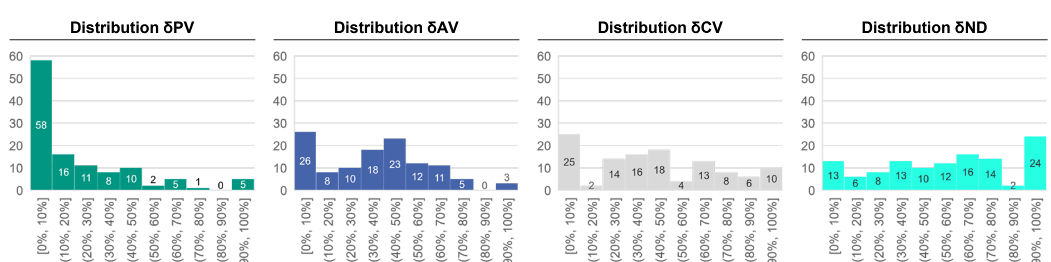

Figure 5: Distribution of variation shares. n=115 due to three baseline generations not counted (c.f. Figure 6). CV: carryover variation, AV: attribute variation, PV: principle variation, ND: new development, δ: share of.

Figure 6 illustrates the cross-generational variation shares for all case studies. Case study 7 stands out as it does not exhibit any CVs. Notably, many case studies show alternating, albeit non-periodic, occurrences of system generations with higher and lower δPV or δND. No cross-case pattern regarding the sequence of variation shares has been identified. In the cross-case analysis, the primary focus was on identifying the mechanisms that led to specific variation phenomena at the overall system and subsystem levels.

Figure 6. Cross-generational variation shares. Unsuccessful generations marked in bolt red.
Case studies 1, 3, 4, and 9 involved the development of partially parallel variants within a product portfolio.

5.3 Heuristics for Design Support Building on Relationships

Heuristics are proven procedures based on experience that can be used for problem-solving, but have no claim to general validity (VDI 2019). The heuristics in Table 3 were derived with a variable-based approach and built on relationships between context factors, SGE, and market success. The heuristics were formulated: *IF* *Description of the development situation* *THEN* *development activity* *[to develop a* G_n *with high innovation potential.]* The last part in square brackets is not repeated in Table 3. A heuristic arising in one case was evaluated in the other cases. Four cases can occur if the "IF" condition is fulfilled:

a) **ITS**: **IF** and **THEN** are fulfilled and the system generation was **Successful** ("if applied, you will win") → Case **proves** the heuristic
b) **InTnS**: **IF** is fulfilled, **not THEN**, the system generation was **not Successful** ("if not applied, you will lose") → **indifferent**, case neither proves nor disproves
c) **ITnS**: **IF** and **THEN** are fulfilled, the system generation was **not Successful** ("if applied, you will lose") → Case **disproves** the heuristic
d) **InTS**: **IF** is fulfilled, **not THEN**, the system generation was **Successful** ("if not applied, you will win") → Case **disproves** the heuristic

In the "type" column, the heuristics were categorized according to their applicability for the development of a product generation $G_{i=n=1}$ without a direct internal predecessor, a generation with at least one internal predecessor $G_{i=n>1}$, and portfolio further development via variants ("P").

Table 3. Heuristics building on relationships between variables. (PP: product profile, CV: carryover variation, AV: attribute variation, PV: principle variation, ND: new development, δ: share of, RSE: reference system element)

Nr.	Heuristic and explanation	Type	a/b/c/d
R01	***IF*** *$G_{i=n-1}$ Macro /Society /Acceptance /low* ***THEN*** *$G_{i=n}$ PV OR $G_{i=n}$ PP PV.* If the acceptance of a product in society is low, then PV to substitute the rejected technology or PP PV to address a different customer group/use case.	$G_{i=n>1}$	3/0/1/0
R02	***IF*** *Customer /Criticism /high regarding subsystem of G_{n-1}* ***THEN*** *AV, PV in the respective subsystem. Residual system CV/low effort AV.* If customers have specific points of criticism, these should be addressed by AV/PV in the next generation. In the remaining system, costs can be saved through CV.	$G_{i=n>1}$	6/0/0/1
R03	***IF*** *Micro /Competition /Competitiveness of the market /high* ***THEN*** *δND high (≥ 50%).* In a highly competitive market, a higher δND is necessary.	$G_{i=n>1}$	35/0/2/16
R04	***IF*** *competitor best in class* ***THEN*** *competitor subsystem as RSE*. Fast follower strategy on subsystem-level through external RSE.	$G_{i=n=1}$ $G_{i=n>1}$	22/0/2/0
R05	***IF*** *Macro /Technology /Availability of new manufacturing technology* ***THEN*** *PV in the respective subsystem*. The integration of new manufacturing technologies requires PV.	$G_{i=n>1}$	1/1/0/1
R06	***IF*** *PP PV* ***THEN*** *PV.* PV in the product profile (different main product goal) requires PV on system level.	$G_{i=n=1}$ $G_{i=n>1}$	20/0/2/1
R07	***IF*** $G_{i=n}$ ***THEN*** *PP Customer Benefit AV or PV.* New/improved customer benefits must be added in every generation.	$G_{i=1}$, $G_{i=n}$,	99/2/14/3
R08	***IF*** *$G_{i=n-1}$ PP PV (first Mover)* ***THEN*** *$G_{i=n}$ δPV < $G_{i=n-1}$ δPV.* After a successful first mover generation, the new PV share can be reduced.	$G_{i=n>1}$	11/0/1/3
R09	***IF*** *Macro /Technology /Availability of new standard /high* ***THEN*** *AV or PV for integration.* Once new technologies have become established as standard, they should be integrated.	$G_{i=n>1}$	12/0/0/1
R10	***IF*** *$G_{i=n+1}$ Macro /Legal /Harshness of regulation /high* ***THEN*** *$G_{i=n}$ PV.* Foreseeable changes to the legal framework should be anticipated through PV in SGE and, if in doubt, overcompensated.	$G_{i=n=1}$ $G_{i=n>1}$	5/0/0/0
R11	***IF*** *Micro /Customer / *new factor** ***THEN*** *PP PV/AV.* If a new key factor arises among customers, the product profile should be adapted.	$G_{i=n>1}$	3/0/1/6
R12	***IF*** *subsystem in $G_{i=n-1}$ PV* ***THEN*** *subsystem in $G_{i=n}$ not PV.* If the subsystem was developed with PV in the $G_{i=n-1}$, PV in the $G_{i=n}$ is not necessary.	$G_{i=n>1}$	122/3/ 13/52
R13.1	***IF*** *$G_{i=n-1}$ not successful* ***THEN*** *$G_{i=n}$ PV high.*	$G_{i=n>1}$	2/3/1/2
R13.2	***IF*** *$G_{i=n-1}$ not successful* ***THEN*** *$G_{i=n}$ PP PV.*	$G_{i=n>1}$	2/4/0/2
R13.3	***IF*** *$G_{i=n-1}$ not successful* ***THEN*** *$G_{i=n}$ δND high (≥ 50%).*	$G_{i=n>1}$	4/2/2/0
R14	***IF*** *$G_{i=n}$ new subsystem then* ***THEN*** *external RSE.* External RSE should be used for a new subsystem/a change in the system architecture.	$G_{i=n>1}$	6/0/0/1
R15	***IF*** *$G_{i=n}$ high-end variant* ***THEN*** *δPV > 0%.* High-end variants always need PV to differentiate themselves internally and externally.	$G_{i=n>1}$ P	8/2/0/5

Only for R10 were no counterexamples (c, d) found. For all other heuristics, at least one counterexample (c, d) was found. These heuristics could now be directly rejected; however, further investigation and potentially more specific situational analysis could provide additional insights. R05 and R13.2 do not yet allow any conclusions to be drawn as more data points are needed. R02, R04, R06, R09, and R14 show a strong tendency towards (limited) confirmation. R01, R03, R07, R08, R12, R15, and R13.3 need to be quantitatively investigated but currently show a tendency towards (limited) confirmation. R11 and R13.1 can currently be rejected.

5.4 Heuristics for Design Support Building on Cases

The heuristics in Table 4 were derived with a case-based approach and are based on observations in individual cases. They cannot be formulated as situational and success-oriented and thus not evaluated as the heuristics in Chapter 5.3.

Table 4. Heuristics building on individual cases. (PP: product profile, CV: carryover variation, AV: attribute variation, PV: principal variation, ND: new development, δ: share of, RSE: reference system element)

Nr.	Heuristic and explanation	Type
C01	*Internalization of RSE for $G_{i=1}$*: When developing a $G_{i=1}$ without an internal predecessor, as many RSEs as possible should be internal to reduce the knowledge deficit and thus the risk. The acquisition of companies ($G_1^{\text{BYD Battery}}$, G_1^{iPhone}) and cooperation with potential competitors and suppliers (G_1^{iPhone}, $G_1^{\text{Playstation}}$, $G_5^{\text{THS-G, Compact - first PHEV}}$) were success strategies, to keep δPV low.	$G_{i=n=1}$ $G_{i=n>1}$
C02	*RSE from other branches for invention*: Even if not a guarantee for success (successful: $G_{3,4}^{\text{SpaceX}}$, $G_{5,6,7}^{\text{Thermomix}}$, $G_2^{\text{UE BOOM}}$; not successful: Google Glass, $G_3^{\text{UE BOOM}}$), RSEs from other industries bring high potential for invention (also from research, but no example in the data).	$G_{i=n=1}$ $G_{i=n>1}$
C03	*Low new development share, high innovation potential moves*: System generations with "elegant" SGE steps that leverage innovation potential with little, targeted use of RSE, AV and PV and use CV to mitigate cost and risk for the residual system.	$G_{i=n=1}$ $G_{i=n>1}$
C04	$G_{i=1}$ with a new product profile (G_1^{iPhone}, $G_1^{\text{THS-G}}$, $G_1^{\text{Thermomix}}$, $G_1^{\text{BYD battery}}$) can develop more freely in the niche at the beginning than $G_{i=1}$ in a competitive market ($G_1^{\text{Playstation}}$, $G_1^{\text{UE BOOM}}$), but the competitive nature quickly equalizes (H03, H04 become relevant).	$G_{i=n=1}$
C05	*Clear SGE leading variant(s) in product portfolios:* Can be high-end (iPhone, $G_1^{\text{THS-G\_SUV}}$) or mid-range ($G_{4,5}^{\text{THS-G\_Compact}}$, $G_{1,2}^{\text{UE BOOM}}$) and change over time. These lead variants contribute RSE to the parallel variants and concentrate the development effort on themselves. "Variant ping pong" on system level was not a successful strategy ($G_{i=3}^{\text{UE BOOM}}$, Ariane).	P
C06	*Inheritance of internal RSE across product lines, especially for $G_{i=1}$ out of own portfolio*. All $G_{i=1}$, except $G_{i=1}^{\text{SpaceX}}$, build on internal RSE from other product lines.	P $G_{i=n=1}$
C07	*Clear differentiation of variants after internal cannibalization.* E.g. true low-end instead of lower-end variant ($G_{12}^{\text{iPhone}} \rightarrow G_{13}^{\text{iPhone}}$)	P
C08	*Successful creation of low-end variants:* A not successful example was the $G_7^{\text{iPhone, lower end}}$. Only CV based on $G_{i=n-1}$ (pure "trickle down") did not prove successful. A better strategy was CV from RSE from parallel high-end variants for important subsystems and save costs through CV in other subsystems through RSE from $G_{i=n-1}$ ($G_1^{\text{UE BOOM, low end}}$, $G_8^{\text{iPhone, low end}}$)	P
C09	*Quasi-parallel vs. sequential launch of product variants*: The often quasi-parallel iPhone launches enabled C08. The sequential launches of THS-G and UE BOOM show the risk of "SGE dead ends" - where subsystems of discontinued or low-end variants with δND cannot be inherited as RSE to other variants. Sequential launch should be combined with C07.	P
C10	Open innovation strategies result in parallel development branches at partners and competitors which can provide valuable external RSE in future generations ($G_5^{\text{THS-G, Compact - first PHEV}}$).	$G_{i=n=1}$ $G_{i=n>1}$

5.5 SGE Evolution Patterns

The SGE evolution patterns can be seen in analogy to the Mendel rules of genetics and describe how reference system elements in the case studies were passed on over generations on subsystem level. These patterns are observations from the case studies and can be understood as options for action in strategic product planning on subsystem level.

Table 5. SGE Evolution patterns. (CV: carryover variation, AV: attribute variation, PV: principal variation, RSE: reference system element)

Nr.	Pattern	Explanation
P01	PV→PV	Rapid development due to high innovation pressure or unsuccessful variation for which a new solution had to be developed.
P02	AV→PV, alternating	High innovation pressure leads to new solution principles being repeatedly implemented through PV followed by optimizations through AV.
P03	PV→CV→CV AV→CV→CV	Successful AV/PV are carried over. With esb RSE the subsystem was a successful fast follower, with edb RSE or PV based on internal RSE a first mover. The redefinition of "Design DNA" also shows this pattern.
P04	CV→CV→PV	PV after longer CV periods can be interpreted as a technological leap.
P05	CV→CV→CV	Longer CV periods show the inheritance of successful subsystems over multiple generations.
P06	CV→AV→CV	Subsystem that occasionally needs to be adjusted - "gradual evolution".
P07	PV→AV→ … →CV	Optimization of a new principle over several generations.
P08	AV→AV→AV	Subsystem that requires continuous adaptation while the principle remains.

5.6 Discussion of Validity

The validity of the results depends on data collection and the data analysis in the cross-case analysis. With at least two people involved in conducting the case studies (student and supervisor), clear definitions of the model of SGE, and the transparency of the process and the sources, we aimed to ensure rigour in the data collection. The case studies, conducted by mechanical and mechatronic engineers, may underrepresent electrical and software perspectives.
The weaknesses of the dataset have been discussed in section 4. Particularly, the "survivor bias" due to the imbalance between successful and unsuccessful system generations poses a problem in the analysis. Due to the qualitative nature of the study, the heuristics and evolution patterns cannot be understood as universally applicable relationships of system evolution. The evaluation across cases in 5.3. allows an initial assessment of validity. In a quantitative study, the heuristics and evolution patterns could be considered and investigated as hypotheses.

6. Conclusion and Outlook

In the study, a research dataset with 14 retrospective, literature-based case studies on the evolution of technical systems based on the model of SGE was generated and published (**objective 1**). Data collection offers automation potential that is already being investigated. For the technical SGE analysis, disassembly databases for retrospective studies and company Product-Data-Management (PDM) systems can provide data. For the context analysis, the World Bank database and web crawling with suitable Natural-Language-Processing (NLP) approaches and Large Language Models (LLMs) offer potential.

Guided by the research question *What relationships exist between context factors, reference-based variation activities (SGE), and market success?* 25 heuristics and 8 SGE evolution patterns which give insights into system evolution were derived in a qualitative cross-case analysis (**objective 2**). These findings were discussed in terms of their validity but can only be conclusively evaluated in quantitative studies with a larger and representative dataset. Business model innovation was considered within the company context and could be described in future studies similar to the technical system with the model of SGE.

By formulating the findings as situational heuristics, the insights can provide guidance in product planning and development (**objective 3**), although they have not yet been developed and evaluated as design support. To reach objective 3, the findings must become effective in development teams. A playbook-based approach that was followed so far has not been successful, which is why the approach of an AI (Artificial Intelligence) assistance system (Co-Pilot) and Agents is being explored further. The prescriptive application of the findings should be supported through foresight approaches and, in addition to historical "evolutionary data", also product usage data.

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Biographies

Albert Albers has been a full professor for product development and head of IPEK – Institute of Product Engineering at the Karlsruhe Institute of Technology (KIT) since 1996. He received his doctorate in 1987 under Prof. Palandan of the University of Hannover. Before his appointment to Karlsruhe, Prof. Albers worked for LuK GmbH & Co. OHG, most recently as head of development and deputy member of the management board. He is a founding and former board member of the scientific society for product development WiGeP, a member of the German Academy of Science and Engineering (acatech), and a member of the Advisory Board of the Design Society. Since 2008, he has been President of the Allgemeiner Fakultätentag (AFT e. V.). In addition, Prof. Albers engages in the VDI and serves on the advisory boards of several companies. In 2016, he and the IPEK team were awarded the Honorary Award of the Schaeffler FAG Foundation for excellent achievements and competencies in science, research and teaching in the technical-scientific field.

Felix Pfaff studied mechanical engineering at the Karlsruhe Institute of Technology (KIT) from 2014 to 2020. Since 2020, he has been a research assistant up at the IPEK - Institute of Product Development at KIT. Since 2025, he leads the research department Advanced Systems Engineering, CAE/Optimization, and Design Methods and Design Management. In his doctorate, he deals with the evolution of technical systems.

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Tobias Düser has been a full professor for product engineering and head of IPEK – Institute of Product Engineering at the Karlsruhe Institute of Technology (KIT) since October 2022. After his studies at the Karlsruhe Institute of Technology and subsequent doctorate at IPEK - Institute of Product Engineering, Tobias Düser held various positions within the AVL Group in the field of innovative development and validation methods. In particular, he worked on novel automation and simulation solutions for test benches. Among other things, he was involved in the development of a new business area, the product portfolio and partner network in the area of Advanced Driver Assistant Systems as well as for Automated Driving. He was a member of the global ADAS/AD leadership circle and also intensively involved in global strategy development. From 2015, he was responsible for the Advanced Solution Lab at AVL and head of the Karlsruhe branch office. In 2020, he additionally assumed global responsibility for ADAS/AD Virtual Testing Solutions. Tobias Düser and his team worked on virtual and XiL-based validation methods for the validation and testing of Advanced Driver Assistant systems as well as for Automated Driving. Furthermore, he participates in various working groups such as IAMTS or UNECE.