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Review of Evolutionary Approaches in Design Research to Support PGE - Product Generation Engineering

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Abstract

In industrial practice, 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.

In design research, multiple approaches such as TRIZ, technical inheritance, and evolution trees use analogies between biological evolution and product development to make knowledge from past product generations usable. The aim of this contribution is to analyze the potential of an evolutionary perspective on PGE to support product developers to develop products with high innovation potential. We first analyzed the analogies between biological evolution and innovation in the context of PGE. We then collected and clustered existing evolutionary approaches. In the next step, we evaluated the extent to which the analogies between biological evolution and PGE are already being used in the approaches from the state of the art. The existing approaches do not offer a complete evolutionary view so far. References are in some form core of the majority of the approaches but the linkage with variation operations and the influence of contextual factors are not consistently considered or explained. Existing approaches support developers in solving specific technical problems. What they do not offer is a fundamental theoretical understanding of the innovation success of products along the lines of the theory of evolution in biology and the latest results in the field of PGE.

Further empirical research based on an evolutionary perspective on the model of PGE could explain relationships between innovation pressure from changing context factors and variation activities. This potential is based on the hypothesis that the evolution of technical systems can be formally described analogously to biological evolution by reference-based variation operators in the sense of PGE influenced by changing context factors.

Keywords: Design Research, Product Generation Engineering, Evolutionary Design, TRIZ, Engineering Design

1 Introduction

Analogy building and interdisciplinary approaches of biology and engineering sciences led several times to successes in research and even paradigm shifts. In the mid-20th century, different aspects of systems theory were combined into the general systems theory by the biologist Bertelanffy, among others (Rosen, 1969). Based on the general systems theory, Ropohl developed the systems theory of technology to describe technical products and processes (Ropohl, 2009). Another example is the science of bionics, which emerged in the 1960s and pursues the technical implementation of effective principles from nature (Nachtigall, 2010).
There are approaches in design research such as TRIZ, technical inheritance, and evolution trees that use analogies between biological evolution, product development and innovation processes (see section 2.4). The core hypothesis 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. Following this analogy, phenomena in the "evolution" of products occur repeatedly in different development contexts. For example, the automation of products and subsystems up to autonomous systems is a common, successful development path in many industries (Kagermann et al., 2017).
Another example is the development of product generations without a direct predecessor, as often occurs in start-ups. More than 90% of all start-ups fail, among other reasons, due to excessive risks in the development of the first product generation. In successful start-ups, similar patterns can be observed in the selection of references and variation activities. (Pfaff, Kubisch, Rapp, & Albers, 2021)
The model of PGE – Product Generation Engineering describes the relations between references and new product generations. The purpose of this contribution is to analyze the potential of an evolutionary perspective on PGE to support product developers. We first analyzed the analogies between biological evolution and innovation in the context of PGE. We then collected and compared existing evolutionary approaches in design research based on purposes and concepts. In the next step, we evaluated the extent to which the analogies between biological evolution and PGE are already being used in the approaches from the state of the art. In the discussion section, we derive potentials for how an evolutionary perspective on PGE can support the development of technical systems with high innovation potential and enable further empirical research.

2 State of the art

2.1 Innovation as a successful invention

According to Schumpeter (1934), innovation is an invention that has been implemented in a product and successfully established on the market (diffusion). Albers et al. specify Schumpeter's definition in the innovation funnel. According to this, three elements are necessary for innovation: Product profile, invention, and market launch. The product profile models the demand situation and explicates the intended customer, supplier and user benefits of the product. The invention, consisting of idea and technical implementation, covers this demand. A successful market launch is the third necessary condition for innovation success. (Albers et al., 2018)
Products and technologies must be adapted and newly developed by product developers in the constantly changing context of law, politics, society, the environment and the market to enable progress and to prevail over the competition. (Arthur, 2009)

In this dynamic context, product profiles and the resulting objectives and requirements for new products must be derived. Up-to-date process models such as the VDI2221 take this dynamic into account with the help of context factors that influence the activities to be carried out. (VDI, 2019)

2.2 Product development from the perspective of Product Generation Engineering

Product development is always a combination of the reuse of successful "old" designs and newly developed subsystems (Shahin, Andrews, & Sivaloganathan, 1999). The model of PGE according to Albers (2015) describes the use of internal and external design knowledge through references based on observations in development practice. The model is based on two fundamental hypotheses (Albers et al., 2015; Albers et al., 2019; Albers et al., 2020):

- Each product is developed based on a reference system R_n (Figure 1). Elements of the reference system (RSE) originate from existing or already planned socio-technical systems and the associated documentation and serve as a basis and starting point for the development of a new product generation G_n.
- The subsystems of a new Product Generation G_n are developed based on the reference system elements (RSE) exclusively by three types of variation (Figure 1): Principle variation (PV), attribute variation (AV) and carryover variation (CV).

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. The modelling of references and variations can be done on the system level, function level and property level (Albers et al., 2020). The characteristics of the RSE and the type of variation are key influencing factors on development targets such as cost, risk, innovation potential, and necessary development activities (Albers, Rapp, Birk, & Bursac, 2017; Pfaff, Rapp, & Albers, 2021).

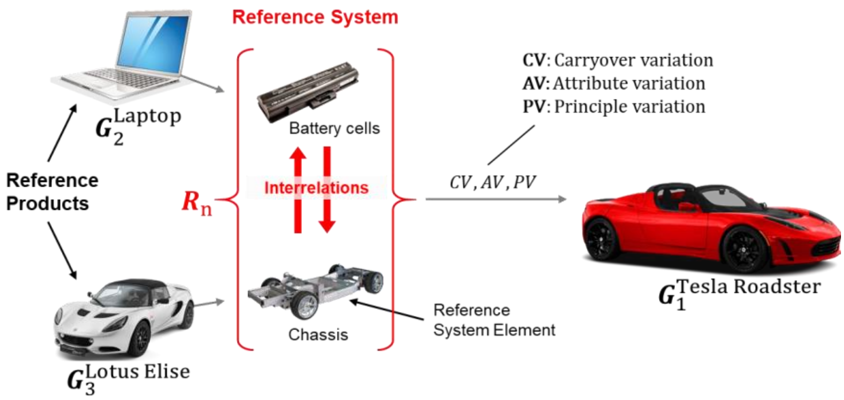

Figure 1: The reference system in the model of PGE (Albers et al., 2019). In the development of the Tesla roadster, the chassis of the Lotus Elise was carried over (CV). The battery cells from the reference product laptop were integrated with a new configuration (AV).

2.3 Basic concepts of biological evolution

Charles Darwin recognized that of several populations, the one that best adapts to constantly changing environmental conditions survives in the survival of the fittest (Darwin 1859). Species and their individuals persist by adapting to new conditions under this evolutionary pressure. The synthetic theory of evolution combines Darwin's findings on selection and Mendel's findings on genetics. The synthetic theory describes and explains the variation of the genetic material of the next generation by random recombination and mutation of the parental DNA. Natural selection determines, from those individuals that evolve from genetic information, those that pass on their genetic material to the next generation. Recent findings extend the model in its basic assumptions and bring other evolutionary mechanisms into the theory of extended evolutionary synthesis (EES). (Laland et al., 2015)

2.4 Evolutionary approaches in design research

A large part of the publications in the context of technological evolution refers to the “Laws of the development of systems” and other approaches according to Altschuller, the “father of TRIZ” (Klein, 2014, pp. 3–4). Altschuller himself does not prominently use the wording “evolution” in his approaches. Other authors do when describing the development and innovation process of technologies, product- or system-generations over a longer period. This section gives a brief overview of evolutionary motivated approaches from design research.

S-curves are used to illustrate and describe the phases that a product passes through over several generations. Altschuller divides the life of technical systems into four sections: Childhood, in which a slow development takes place. Maturity, with a rapid improvement in the maturity level and the start of mass application. Decline, in which the pace of development declines. Age, when either stagnation in sales sets in or replacement by a successor takes place. (Altschuller, 1986, pp. 115–120)
To derive measures for the further development of a technical system, it must first be clarified in which stage it is currently located (Bingquan, Lingxin, Likai, & Yi, 2010). Manabu Sawaguchi (2011) offer recommendations for the respective phases.

Evolutionary laws also go back to Altschuller. Altschuller derives eight laws of the development of technical systems from the analysis of over 20.000 patents. E.g. law two: Law of the "energetic conductivity" of a system: *"A necessary condition for the viability of a technical system is the energy flow through all parts of the system."* (Altschuller, 1986, p. 125) Zlotin and Zusman (2013) revise Altschuller's laws based on patterns observed in technical history studies. Klein (2014) extensively revises the laws of development and assigns them to the phases of the S-curves. These laws claim to apply to the development of technical systems in general, which is why they are formulated in a very general way. Moore's law can also be understood as such a law of evolution for integrated circuits.

An **evolutionary trend** can be understood as the direction in which an evolution proceeds. These trends are used to derive development paths for the future based on previous developments (Klein, 2014, pp. 18–19). These trends are formulated more specifically than laws and apply to certain technical systems. The literature knows a large number of such trends - Zeihsel et al. (2013) mention a collection of 460 “lines of evolution”.

Innovation principles are basic technical solution principles, which have often led to technical solutions and therefore represent promising search directions (Klein, 2014, pp. 49–50). As part of the original TRIZ, Altschuller (1986) formulates 40 such principles, which are later supplemented by other authors (e.g. Klein, 2014; Mann, 2003; Zlotin & Zusman, 2013).

The **algorithm for solving invention tasks - ARIS**, is a guideline for solving invention tasks. The guideline includes step-by-step instructions to identify and solve physical contradictions in subsystems using the above development laws, trends and innovation principles (Altschuller, 1986).

Directed Evolution, originally developed by Zlotin and Zusman, proposes an innovation process in 5 steps to make use of laws, trends and innovation principles. 1) analysis of the present system, 2) analysis of the past/predecessors of the system, 3) brainstorming (based on identified "patterns") and initial risk assessment, 4) decision making: creation of detailed evolution scenarios, 5) realization of the evolution scenario. (Zeihsel et al., 2013)

Evolution trees are used to display trends, patterns, and technical and patent information in an organized manner. It provides an overview of the evolution of a technical system in a tree structure. Trends are represented as tree branches and characteristic product generations are represented as nodes along the branches. It can be used to avoid competing patents or to predict the evolution of a technical system. (Shpakovsky, 2006)

The **Contradiction-oriented innovation strategy – WOIS** according to Linde (1999) is structured in three phases: 1) Orientation, 2) Contradiction - breaking through the development barrier, 3) Solutions behind the development barrier. WOIS exploits contradictions to break through them, taking a shortcut from the "evolutionary spiral" of ongoing optimization. (Linde et al., 1999)

Technical inheritance is defined as the transfer of collected and verified information from the production and usage of a product to the next generation. Its focus is on mechatronic machine elements that collect data e.g. on load cases and maintenance intervals over the entire product life cycle and "inherit" it to the next product generation. Genetic or evolutionary algorithms are recommended for the optimization of the components based on the collected information. (Lachmayer et al., 2014)

The **Autogenetic Design Theory (ADT)** describes design tasks as complex optimization problems for which evolutionary algorithms can be used to find optimal design solutions. Knowledge from previous generations is incorporated into the optimization process via starting objects. (Vajna, Clement, Jordan, & Bercsey, 2005)
“The result of the ADT is a set of equivalent, but not similar unique solutions that fulfil the actual state of requirements and conditions best.” (Vajna, Kittel, & Bercsey, 2011)

Dominant design is less a solution approach and more the description of an evolutionary phenomenon. Technologies and products are not fully developed right from the start. In the beginning, there is a phase of experimentation and concurring solution approaches until a dominant design is established. One of the existing solutions prevails and takes a dominant role in the market and product development. (Henderson & Clark, 1990)

3 Research aim and research design

Section 2.3 shows different approaches from design research that, to some extent, use the analogy between product development, innovation processes (section 2.1) and biological evolution (section 2.3). The aim of this contribution is to analyze the potential an evolutionary perspective on PGE to support product developers. For this aim, the following research questions (RQ) were answered:

- RQ1: What are the similarities and differences between biological evolution and innovation in the context of PGE?
- RQ2: How can the existing evolutionary in design research approaches be compared?

- RQ3: What is the potential for applying the existing evolutionary approaches from design research and core concepts from biological evolution in the model of PGE to support the development of products with high innovation potential?

We answered RQ1 through a tabular analysis of similarities and differences of PGE and the synthetic theory of evolution (section 4.1). To answer RQ2, the evolutionary approaches from the state of the art were compared and clustered based on common purposes and concepts. To answer RQ3, we analyzed based on the results of RQ1 and RQ2 the extent to which the analogies between the synthetic theory of evolution and PGE are already being used in the approaches from the state of the art.

4 Results

4.1 Comparison of the synthetic theory of evolution and PGE

We compared biological evolution (based on the assumptions of the synthetic theory, see section 2.3) and innovation in the context of PGE. The comparison resulted in Figure 2 and five concepts which serve as comparison criteria:

1) Operators for variant creation and use of references
2) Influences of contextual factors which lead to evolutionary/ innovation pressure
3) Adaptation to changing contextual factors
4) Origin of references
5) Timescales

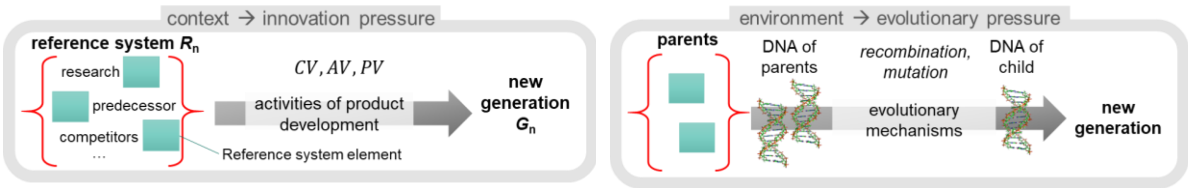

Figure 2: Conceptual comparison of product development and synthetic theory of evolution regarding references, variation, contextual factors and generations

Product development from the perspective of PGE is that new product generations are developed through variations based on the reference system R_n. To develop successful products - innovations - product development activities such as the decision for and implementation of variations must be selected based on the changing contextual factors. Analogous to the reference system, in biological evolution the parents and their genetic material in the form of DNA form the starting point. By random recombination and mutation of parental DNA, variation occurs and the DNA of the new child generation is created. A more in-depth comparison based on the same model elements led to the comparison in Table 1 (further similarities) and Table 2 (differences). Besides differences such as time scales, the origin of references, and the influence of the human factor, the similarities show potential for descriptive models in design research. The theory of evolution in biology describes and explains mechanisms for how the influence of contextual factors and the operators for variant creation interact.

Table 1: Similarities in the analogy of biological evolution and PGE

Concepts	PGE	Synthetic theory of evolution
1) Operators for variant creation and use of references	Variation types, with which reference system elements are mapped to the subsystems of the new generation.	Recombination, mutation, with which the genes of the parent generation are inherited, varied and transferred to the new generation.
2) Influences of contextual factors which leads to evolutionary/ innovation pressure	Selection of products through market mechanisms and solution alternatives for development generations in the development process.	"Survival of the fittest": The species that best adapt to constantly changing environmental conditions survive.

Table 2: Differences in the analogy of biological evolution and PGE

Concepts	PGE	Synthetic theory of evolution
3) Adaptation to changing contextual factors	The creative human developers develop new product generations through the targeted selection of references and variation types for subsystems. This results in everything from low to high new development shares in subsystems from generation to generation.	Random emergence of variants in natural evolution without deliberate selection by humans results in gradual changes from generation to generation.
4) Origin of references	Reference system elements can be chosen by the developers from internal or external sources.	References are limited to the parents.
5) Timescales	Time in market and development times strongly dependent on industry, often several years.	Evolutionary processes in nature have been taking place for millions of years and over many generations.

4.2 Comparison and clustering of the evolutionary approaches

We assigned **evolutionary laws**, **trends, innovation principles, and evolution trees** to the cluster *evolutionary knowledge storage*. All approaches aim to support the development of new products with condensed knowledge about past developments. The approaches can be characterized by their degree of concretization and their general applicability (Ohmer, 2008). Approaches of classical design methodology, ordered by increasing general applicability, are design rules, design guidelines, design principles and the basic rules of design (Kirchner & Neudörfer, 2021). Other examples of very specific design support are solution collections or design catalogues, which provide recurring partial solutions for specific design problems in a clear form (Roth, 2001). In comparison to these classical approaches, we mapped the evolutionary approaches (Figure 3).

Evolutionary laws claim to apply to the development of technical systems in general, which is why they are formulated abstractly. The various versions of the laws of evolution each represent interpretations, modifications, and extensions of Altschuller's original eight laws. Evolutionary trees are formulated for specific technical systems. Therefore, we classified them as rather specifically applicable and concretely formulated. Evolutionary trends span a wider area in the graph. The more abstractly formulated, the more generally applicable they are. Altschuller's innovation principles have proven to be generally applicable in technical problem-solving. At the same time, they are formulated in a concrete manner, which benefits their applicability.

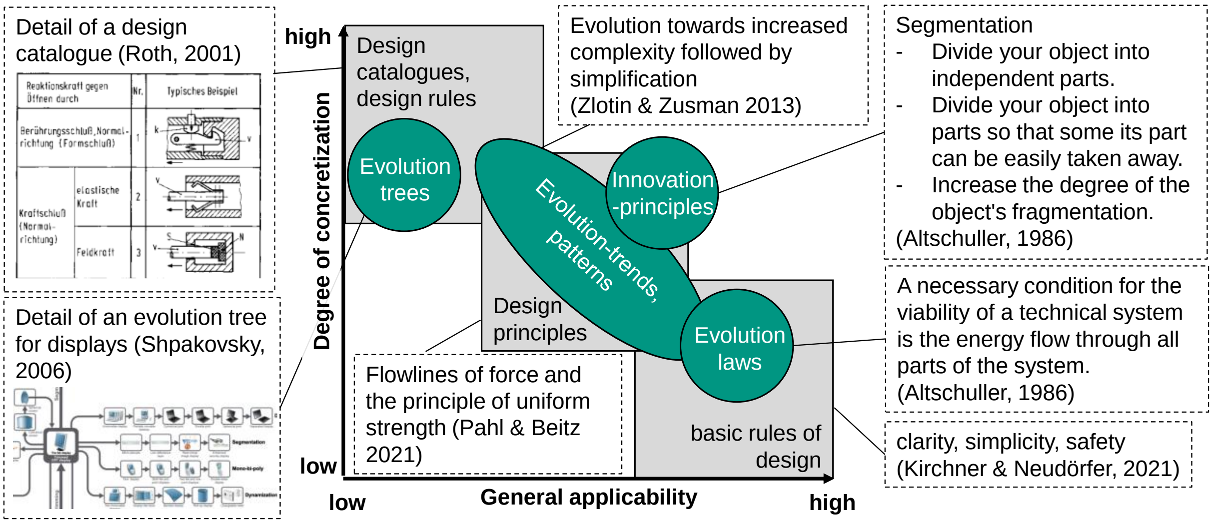

Figure 3: Qualitative comparison of the approaches of the cluster evolutionary knowledge management regarding applicability and concretization. Approaches from classical design theory are given as a reference.

The three approaches **ARIS**, **Directed Evolution** and **WOIS** were assigned to the cluster *methodical approaches*. They specify processual and methodical support for the solution of specific technical problems, but with different focuses.

- ARIS: Solving specific technical problems using a strongly formalized, step-by-step approach.
- Directed Evolution: "Evolutionary" development of technical systems with a software tool as a guide and support.
- WOIS: "Evolutionary" development of technical systems by uncompromising overcoming of contradictions.

In all three, the approaches which we assigned to *evolutionary knowledge management* are used for system analysis and solution-finding.

The **technical inheritance** approach and the **ADT** form the fourth cluster *algorithmic design*. Both use the evolution analogy to turn the design task into an optimization problem. ADT considers the design task in general, TI the use of data from the product life cycle in particular. **Dominant design** and the **S-curve** could not be assigned to any further Cluster.

4.3 Analysis of the use of the evolution analogy in existing approaches

We refined the five concepts from section 4.1 based on the results of the comparison to analyze the clustered evolutionary approaches from section 4.2 regarding the use of the evolution analogy:

- Use of references as a starting point for variation
- Consideration of references from various origins
- Operators for variant creation
- Consideration of contextual factors
- Relation of contextual factors and variations

The approach of Dominant design was not included in the comparison as it just explicates a single phenomenon. We summarized the result of the analysis in table 3. All approaches of the cluster *evolutionary knowledge management* use references. Some of the evolutionary laws and

evolutionary trends presuppose the comparison to RSE e.g. Altschuller's law 5: non-uniformity of the evolution of the parts of a system (Altschuller, 1986, p. 127). Evolution trees consist of trends and references which represent these trends.
The three approaches of the cluster *methodical approaches* use references as part of their solution-finding and system analysis steps. References mainly occur indirectly via the standard solutions or directly when compared with problems that have already been solved. All approaches of the clusters *evolutionary knowledge management* and *methodical approaches* use references from various origins, where direct predecessors always play a central role. For the optimization processes in the cluster *algorithmic design* existing solutions are needed as references to start the process of optimization. Technical inheritance and S-Curves only consider predecessors, while the ADT also considers external references as input.

Operators for variant creation starting from references are not a central component in any of the approaches. The innovation principles can be seen as operators to some extent, but do not achieve the necessary degree of formalization. Technical inheritance and ADT specify genetic algorithms as the method to use for the optimization of the next generation.
Contextual factors are directly considered in the approaches Directed Evolution and WOIS. Evolutionary laws, trends and the S-Curve consider contextual factors for the formulation of regularities. Some evolutionary laws and trends formulate causal relationships between contextual factors and variations in technical systems.

Table 3: Comparison of the approaches regarding the evolution analogy.
Legend: ✓ fully considered, (✓) partially considerd, - not considered

	Use of references as a starting point for variation	**Consideration of references from various origins**	**Operators for variant creation**	**Consider-ation of contextual factors**	**Relation of contextual factors and variations**
Evolutionary knowledge management					
Evolutionary laws	(✓)	✓	-	(✓)	(✓)
Evolutionary trends	(✓)	✓	-	(✓)	(✓)
Innovation principles	✓	✓	(✓)	-	-
Evolution trees	✓	✓	-	-	-
Methodical approaches					
ARIS	✓	✓	-	-	-
Directed Evolution	✓	✓	-	✓	-
WOIS	✓	✓	-	✓	-
Algorithmic design					
Technical inheritance	✓	-	(✓)	-	-
ADT	✓	✓	(✓)	(✓)	-
Other approaches					
S-Curve	✓	-	-	(✓)	-

5 Discussion and outlook

We derived potentials for design support in PGE from the results of the comparison of biological evolution and PGE, and the analysis of existing evolutionary approaches in design research. The approaches from the cluster *methodical approaches* use evolutionary knowledge from past successful products to support product development. In these methodical approaches, evolutionary knowledge e.g. represented through trends and innovation principles (cluster *evolutionary knowledge management*) is used to solve technical problems on anticipated future needs and boundary conditions. This core concept of using evolutionary knowledge also offers potential for further empirical research and application in PGE: the model has a high degree of formalization and a mathematical model to describe product development processes. This description is possible on embodiment level, function level, and property level. Due to the high degree of formalization and the adaptable degree of abstraction, the model of PGE enables the retrospective and accompanying collection of data of the reference- and variation-based development of product generations. This data can lead to further evolutionary knowledge, into how products are developed based on references to fit certain contexts.

The comparison of the existing approaches regarding the evolution analogy shows that the approaches do not offer a holistic evolutionary view so far: existing evolutionary approaches support developers in solving technical problems. What they do not offer is a fundamental theoretical understanding of the evolution of products in their product context. Especially the relations between changing contextual factors, innovation success, and reference-based variation activities are only partially investigated. Further empirical research based on an evolutionary perspective on PGE could explain relationships between innovation pressure from changing context factors and variation activities. This could allow the development of methods to respond, for example, to innovation pressure caused by customer needs or political actors. By systematically carrying over successful reference system elements into new product generations or systematically varying embodiment or principle design where it causes the highest innovation potential.

This potential is based on the hypothesis that the evolution of technical systems can be formally described analogously to biological evolution by reference-based variation operators in the sense of PGE influenced by changing context factors. A question that needs to be answered to further investigate this hypothesis and leverage the described potential is how the changing context can be described alongside variation activities in the model of PGE.

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