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# A Framework for Defining Innovation in the New Development of Modular Product Families

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**Abstract:** The development of new products poses a particular challenge due to the increasing complexity of markets, organizations and product development. This contribution aims to support the new development of modular product families by considering aspects of new product development and innovation. Various concepts and dimensions of innovation in relation to product development and modularity are examined. Based on the dimensions of external and internal variety and different degrees of novelty, the Product Family Innovation Matrix (PFIM) was developed to support the development of innovative modular product families. Four different change mechanisms were systematically compared and classified in the PFIM together with innovation approaches from the literature, resulting in a strategic support tool for the new development of modular product families.

*Keywords: New Product Development, Innovation, Modular Product Families, Product Architecture Design*

## 1 Introduction

Continuous change is the main driving force behind many development activities. The world seems to move faster, new-product projects must be accelerated to market, while markets and needs are not stable for long (Cooper, 2022). At the same time, new technologies enable improvements, but also require new knowledge. Many physical products are becoming increasingly intelligent and connected (Cooper, 2022). Among other things, this requires the development and integration of software, which brings additional complexity to development projects. This poses new challenges for product development. New practices, methods and processes are needed to meet these challenges, which require interdisciplinary development activities and new organizational knowledge, e. g. for the integration of software and service solutions as well as the consideration of different regional aspects and sustainability requirements (Marzi et al., 2021). This change is leading to increasingly complex products, product-service systems, intelligent products, production systems and more (Marzi et al, 2021; Mertens et al., 2022).

Modularization methods and, from this point of view, the development of modular product families have proven to be useful for handling high complexity, especially in the case of high product variety and the resulting variance-induced product and system complexity (Krause and Gebhardt, 2023). Within approaches for handling existing complexity, there is a lack of support for initial system development and the integration of an innovative character (Sankowski et al., 2021). In the German literature, suitable development methods for products and mechatronic systems are provided with e. g. the Verein Deutscher Ingenieure (VDI) 2221 (VDI, 1993) and VDI 2206 (VDI, 2004) - internationally, approaches such as the Stage-Gate Process for new product development (Cooper, 2022) and Design Thinking for business innovation have become established (Kwon et al., 2021), but these lack consideration of modularity and product variety (Küchenhof and Krause, 2019). However, the links between product and process modularity and the development of new, innovative products are ambiguous and not clear (Mertens et al, 2022; Xiao and Zhang, 2020). The new development of modular product families, taking into account new needs structures as well as technological inventions and thus leading to innovations, represents a gap in the field of methodical development of modular product families.

This contribution aims to support the new development of modular product families by taking innovation aspects into account. The research approach used is based on the Design Research Methodology by Blessing and Chakrabarti (2009). First, the research questions are formulated. The research background summarizes a preliminary descriptive study to answer the first research question. This is followed by a prescriptive study in which a strategic instrument to support the classification of innovations in the context of market, technology and modularity is presented. Finally, the methodological framework is linked to existing innovation strategies from the literature. The research questions are as follows:

*RQ1: What are the identified dimensions of innovation in new product development and modular product families as documented in the existing literature?*

*RQ2: How can these dimensions be used to assess the innovation potential of modular product families and contribute to the understanding and improvement of innovation processes related to the new development of modular product families?*

In the following Section 2, the first research question is answered by introducing an understanding of the development of modular product families and then presenting different approaches from the literature with relevance to product architecture development and innovation. Relevant dimensions that could be identified are derived from this. In Section 3, the two essential dimensions for the development of modular product families "external and internal variety", are opposed in the Product Family Innovation Matrix (PFIM). Along with mechanisms of change the PFIM is transformed into a strategic support tool for the new development of modular product families to address the second research question. Finally, Section 4 draws a conclusion and provides a brief outlook on further possible research activities.

## 2 Research Background

In the following, the fundamentals for the development of product families and modular product design are introduced. Various types of innovation from the literature are presented below.

### 2.1. Development of Modular Product Families – External and Internal Variety

Modularity can be understood in different ways. Explanations usually lead to products or systems with different partitions and the ability to easily exchange components through defined interfaces. Salvador (2007) gives a more detailed definition by indicating different perspectives on modularity: component commonality, component combinability, function binding, interface standardization and loose coupling. In view of these perspectives, modularity is not a binary value, but a gradual characteristic in which some perspectives are more or less strongly emphasized. The development of modular products can help to manage a high level of complexity (Krause and Gebhardt, 2023). This complexity can come from various sources, such as the market with standards, laws and competitors, organizational factors such as the people involved and their relationships, the production process or division of labor, or the product itself (Lindemann et al., 2009). A common classification is the distinction between external and internal factors (Lindemann et al., 2009). With focus on variance-induced complexity, the Integrated PKT-approach for the development of modular product families aims to satisfy a high external offer variety with a low internal component and process variety thus reducing the overall complexity (Krause and Gebhardt, 2023). Two main methods of the approach are Design for Variety (DfV), in which a product family is restructured in such a way that an existing external variety can be offered with a reduced internal variety, i. e. of components. This is followed by modularization, which includes technical-functional modularization, in which interfaces are defined in terms of physical dimensions, and product-strategic modularization, in which module cuts not only serve the working function of a product, but rather take into account different perspectives (Krause and Gebhardt, 2023). Modularity can enable not only economies of scale through standardization, but also economies of scope through the creation of advantages in production or for end-of-life processes such as reusability or recyclability (Mikkola, 2006). Taking into account product variety and different perspectives including other product life phases from the very beginning of product development, Küchenhof and Krause (2020) provide methodical support for the new development of modular product families. This has been expanded to include digital aspects as part of the consideration of cyber-physical systems (Küchenhof et al., 2022).

### 2.2 Types of Innovation

Innovation can also be understood in different ways. Usually, innovation describes the realization of a novel and progressive solution for a certain problem in form of a product that is successfully launched on the market (Ehrlenspiel and Meerkamm, 2013). Based upon this definition, different contexts and perspectives on innovation exist.

Kobe sees two possible sources for new product ideas and product improvements, which can be roughly divided into two groups: Sources of new customer requirements and needs - i. e. problems to be solved (market) and sources of new solutions to problems (technology) (Herstatt and Verworn, 2007). The search for innovation ideas can therefore be understood as a combination of problems and requirements with the appropriate technical solutions. Small, incremental and large, radical innovation steps are possible for both the requirements/problems and the technologies (Herstatt and Verworn, 2007).

Henderson and Clark (1990) propose a framework where they classify the impact of different kinds of innovation on the capabilities of the firm in two dimensions. The first dimension is the core concept of the product which may be reinforced or overturned. The link between core competencies and components may be changed or not. The juxtaposition of these two results in the classification in incremental, modular, architectural and radical innovation (Henderson and Clark, 1990).

Often, innovation projects may differ in their type based on their degree of technical uncertainty and market uncertainty (Herstatt and Verworn, 2007). The uncertainty matrix from Lynn and Akgün (1998) assesses the technical uncertainty and the market uncertainty, which both may be low or high. Following their understanding, incremental innovations build on existing knowledge. Market innovations open up new markets with known technologies. Technical innovations serve known markets with new technological solutions. The greatest degree of uncertainty in both market and technology may lead to radical innovations (Herstatt and Verworn, 2007).

The understanding of innovation according to Kalogerakis et al. (2010) is based on the concept of transfer distance and transfer content. Innovations are not assumed to be fundamentally new, but that new ideas are usually based on analogies that are described in relation to their source in terms of transfer distance and transfer content. can be described in terms of transfer distance and transfer content. The transfer distance describes the distance of the analogy between the source and the target. According to this understanding, the transfer distance is small or large if the transferred problem solution is located in the same application context as the target problem or in a different one. The solution-specific knowledge can come from the same product category, from a different product category or from a non-product knowledge area. The greater the transfer distance, the greater the potential novelty of an analogy. The transfer content describes the type of knowledge that is transferred from the basic domain to the target problem. The transfer of technological solutions or functional principles and of forms and design arrangements is considered here (Kalogerakis et al., 2010).

Innovations may also differ in terms of who is capturing and who is creating the value. Chesbrough and Appleyard's (2007) concept of open and closed innovation divides into in-house and community-driven value creation. The value capture can differ in terms of the value being realized by a company or an ecosystem like a larger community. In more classical concepts, value capture and creation both lie within a company. Platforms like Youtube, Instagram and Tiktok use value created by the community while the value is captured by the company. An example for community-driven value creation which can be used by a whole ecosystem are open-source products like Linux and Wikipedia (Chesbrough and Appleyard, 2007). Enkel et al. (2020) present a maturity framework for open innovation where companies can assess their position in terms of their openness. The three different key roles are traditionalist, modernist and visionary, depending on whether the company is more closed and does not integrate outside experience or is a virtuoso in appreciating ideas and perspectives from different ecosystems (Enkel et al., 2020).

Ehrlenspiel and Meerkamm (2013) implement a risk management strategy in the Ansoff matrix. Ansoff differentiates whether a market exists or if it is new and if the product already exists or not. Four strategies emerge in the Ansoff matrix that are a market penetration, product development, market development or diversification strategy (Ehrlenspiel and Meerkamm, 2013).

### 2.3 Dimensions of Innovation in New Product Development

Different perspectives on innovation have been described above. In order to answer RQ1, i. e. which dimensions of innovation are considered in the literature, it can be summarized that market and technology, uncertainty, value capture and value creation, openness and risk play an essential role within the development of new products. It is also visible that the development of modular product families is based on technological assumptions, with the market view being added to Ulrich's functional-structural product architecture design (Ulrich, 1995), including the Integrated PKT approach. External and internal complexity play a decisive role in the design of complex products (Lindemann, 2007). External and internal variety are essential for the design of modular product families (Krause and Gebhardt. 2023). However, no coherent approach to the innovation of modular product families has been found in the literature that takes external and internal variety into account. Product architecture has been considered in the development of new products and with regard to innovation, but more as a structural component of innovation processes than as a strategic tool.

## 3 Finding the Green Field – Novelty Types within the Development of Modular Product Families

External an internal variety play an essential role in the development of modular product families. In the context of the new development of modular product families, the aim is to assess the innovation potential of product development projects in both dimensions and to provide strategic implications based on this. These implications are derived by mapping existing innovation approaches to the resulting novelty types.

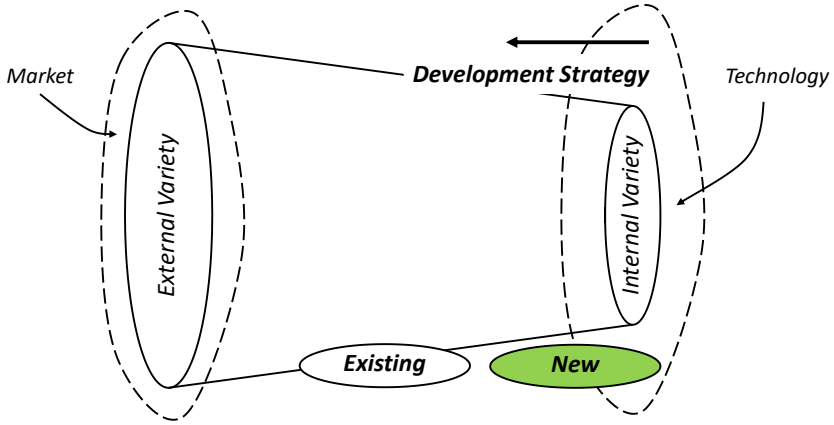


Figure 1. Domains of external and internal variety within the development of modular product families

Figure 1 shows a visualization of the external variety on the left and internal variety on the right. External variety describes a company's market offering embedded in a competitive environment, i. e. the product variants sold on a market. Internal variety describes the corporate measures taken to satisfy the external variety, i. e. components and processes in a company to produce the product variants. Internal variety is also embedded in a surrounding environment, whereby the technological perspective is adopted here. Both the external and internal variety are further differentiated into the states *Existing* (white) and *New* (green) in order to establish a link to new development projects. Development strategies that indicate the direction of transformation are symbolized with black arrows.

Based on the different innovation dimensions of external, internal, existing and new, the Product Family Innovation Matrix (PFIM) was developed, which is shown in Figure 2. The matrix combines the dimensions of external and internal variety with the degree of novelty of the market and technology side.

When determining the degree of novelty, a distinction is now made not only as to whether it is something known or new, but also for whom it is known or new – components can, for example, be categorized as standard or new to the firm (Mikkola, 2006). Projects can be considered in the context of world novelty projects (Marzi et al., 2021) and thus be new not only to the company but also to the whole environment. Thus, the attribute *New* is further subdivided into the characteristics *New to the Company* (NTC) and *New to the World* (NTW). An external variety that is offered on an existing market is *Known/Existing*. New product variants can be offered on an existing market - the products offered by the company are in this case NTC, but not explicitly NTW. Markets are either known or unknown, and they may or may not exist, but these are not mutually exclusive. A market may be known to others but not to the company, and is therefore NTC but not NTW. Some markets do not yet exist. They must first be created and are by definition NTW. If new product variants are to be introduced in non-existent markets, this is the case of NTW with the highest degree of external novelty. Products that are NTW must therefore also be NTC.

On the internal side, the components and processes used to manufacture existing product variants are referred to as *Known/Existing*. The (re)use of existing facilities and assets as part of product development in the manufacturing industry is also known as the brownfield process (Pakkanen et al., 2016). If a company had to adapt or introduce technologies that are already used by other companies or competitors in order to create future product variants, the technology side in this case would be NTC, but not NTW. If completely new components or processes have to be developed in order to create future product variants, these would fall under NTW. Developed technologies that are NTW are by (this) definition also NTC, as they did not exist anywhere before their development. The comparison of these three degrees of novelty of external and internal variety and their combination leads to the 3x3 PFIM. The various types of novelty resulting from the combination of external and internal domains are described in the following.

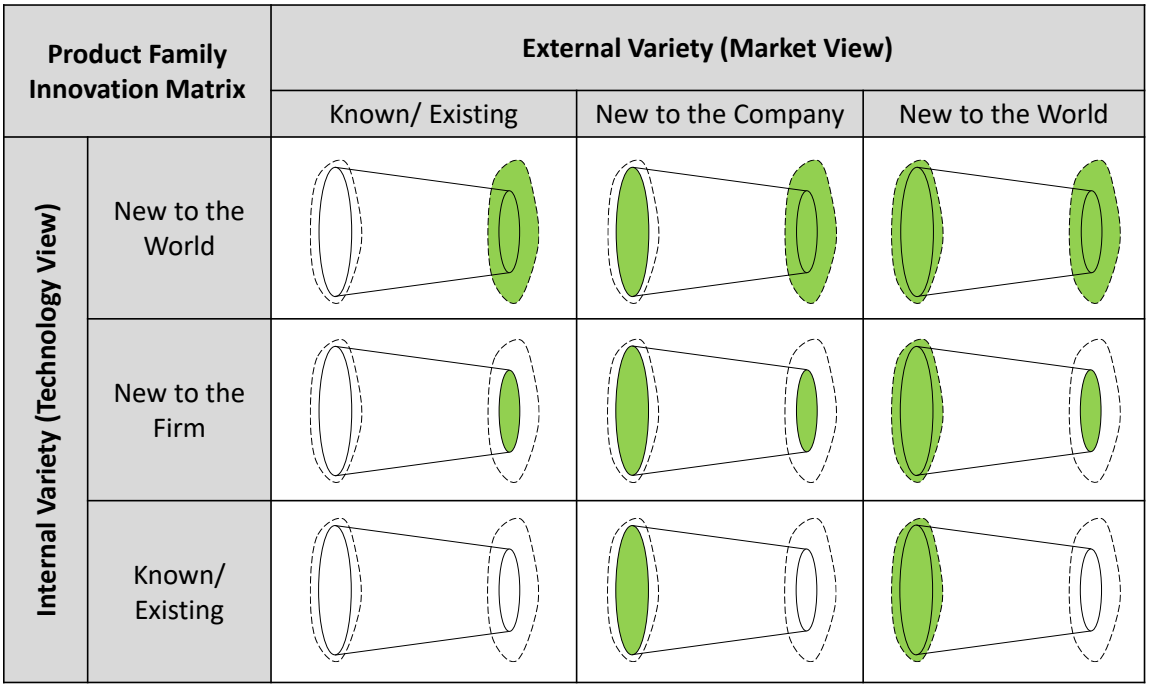


Figure 2. Product Family Innovation Matrix - Combination of novelty aspects in the two dimensions of external and internal variety

**Left column – Known markets**

In the lower left sector, an existing product solution is to be offered in already served markets. Neither external nor internal variety are planned to be changed in the future. A company may want to develop a new internal variety or introduce new manufacturing processes to satisfy an existing external variety. Depending on the novelty of the solution, it may be NTC but already known for competitors (left middle) or a technological world first (left top).

**Center column – New to the Company markets**

In contrast to the left-hand column, external variety is subject to change in the cases in the middle column. In future, this may mean offering new product variants within a market segment already served or opening up new market segments for the company. If this is to be done with an existing internal variety of components and processes, the picture in the middle column at the bottom results. If the internal variety is also changed, the case in the middle results. Here, both external and internal variety are NTC. If NTW technologies and components should be developed, the case in the middle at the top results.

**Right column – New to the World markets**

In the right-hand column, new markets are to be created. This can be done by introducing established components and technologies with a new purpose to new target markets. Or by creating new product variants by recombining the existing internal variety, as existing components or modules and processes. Since no further internal development is required, a significant advantage can arise. If internal variety has to be adapted, the case in the middle results. If a world-first technology needs to be developed on component or process side, the case at the top right is the result which represents the case with highest degree of external and internal novelty. Here, a high level of uncertainty and risk needs to be accepted.

With the help of the PFIM, the external and internal degree of novelty of a development project can be assessed. Instructions for action and strategies to get from the source to the target are then desirable. To do this, two things need to be established that are not evident in the PFIM. One is the identification of the current situation of the company. Some cases can be covered by logical reasoning, others require further support in the assessment. If there is an existing external variety (product offer), there must also always be an existing internal variety (components and processes) (cases in the left-hand column). Also, there exists an internal variety for all three cases in the bottom row per definition. The right-hand column indicates that the markets do not yet exist - this means that there can be no current market shares for the company. In the case of NTC shares, however, it is not clear in the PFIM whether a new variety is to be created or an existing variety is to be changed. This situational assessment requires further support, which is aimed at in the following with the help of change mechanisms. The second question is what strategies could be used to achieve the desired development goal. Depending on the combination of change mechanisms, the current situation can be assessed and strategic action measures can be derived and assigned to the PFIM cells.

### 3.1 Change Mechanisms of External and the Internal Variety

Development activities lead from an original state to a desired state. The PFIM does not show the change in state of the external and internal domain, but can help estimate the degree of novelty of an innovation project before the actual development takes place. Both, the external and the internal domain can be subject to change during development. Different change mechanisms can affect the domains, four of which are deduced and shown in Figure 3. The first change mechanism is *No Change*, where the previous and subsequent states are the same. An *Expansion/ Contraction* extends or shrinks an existing domain by certain portions, which are colored in green. The black arrow indicates the direction of the change. In the case of a *Shift*, a new direction is sought on the basis of the existing shares. The last change mechanism is *Creation*, where no direct predecessors exist. In this case, the domain must first grow or be developed.

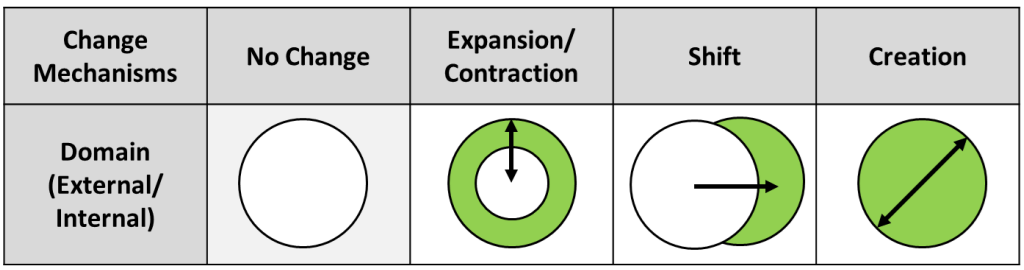


Figure 3. Change mechanisms considered for the development of innovative product families

The four change mechanisms are now applied to external and internal variety and then juxtaposed. This results in 16 different situations, which can be seen in the matrix of combinations of change mechanisms in Figure 4. Each situation can be regarded as a development case. To handle the different cases, different strategies can be used based on the necessary development activities implied by the change mechanisms. In the following, the focus is on the difference

between existing and new. When combining change mechanisms, no distinction is made between NTW and NTC, as the matrix becomes too complex and the mixed forms become very theoretical, but not more comprehensible.

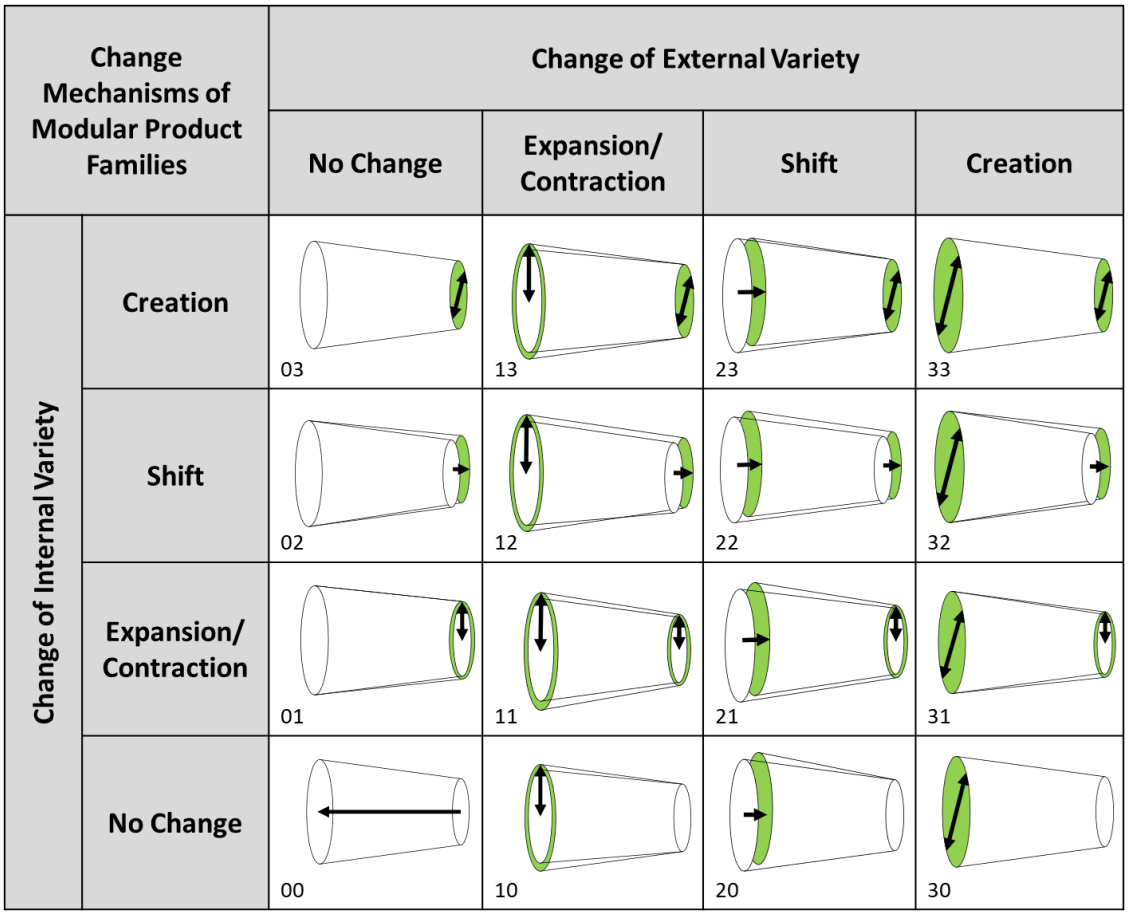


Figure 4. Matrix of 16 combinations of change mechanisms in the development of innovative product families

**The Diagonals**

The pure forms of the combination of change mechanisms of external and internal variety are arranged on the main diagonal (00, 11, 22, 33). At the bottom left, neither external nor internal variety is subject to change (00). According to Ansoff, a market penetration strategy can be applied in order to strengthen existing markets with existing products (Ehrlenspiel and Meerkamm, 2013).

With the next change mechanism *Expansion/ Contraction* an existing external and internal variety should be changed in certain aspects (11). According to Ansoff's product strategies, the combination of a market development and a product development strategy could call up innovation potential. Here, the source and target markets are the same. The expansion of an existing external variety could be achieved through individualization (Vogt et al., 2024), integration and implementation of digital components (Zuefle et al., 2022) or product service systems (Rennpferdt et al., 2024) are examples of such an expansion of the existing product range, which also requires expansion of internal variety. It is also possible to reduce the product range if the product variance has cannibalistic effects and differentiation in the market is no longer clear. Reducing external variety can help to develop a product family for a niche market. It can be products that fulfill fewer needs, to the point that a product family is cheaper than competitors', possibly paving the way for disruptive innovation.

(22) A *Shift* in external variety can be understood as the addressing of a new market segment or a different market with sufficient similarity (based on an existing product offer). The internal shift means an equivalent change in internal variety - i. e. the adaptation of existing products to the requirements of the new market segment or market. This comprises company internal components, technologies and processes. Again, a market and a product development need to be considered to make innovate improvements. A *Shift* can possibly be methodically supported with concepts based on analogies. The concept of transfer distance and transfer content according to Kalogerakis et al. (2010) could help with the characterization of innovation projects.

The fourth pure change mechanism combination considered is *Creation* (33). Even though expansion and shift contain or must take into account creative elements, external creation means that there is no external variety in a market or market segment to start with. For internal creation, this means that there are no components, processes or underlying technologies within the company for a product. On the diagonal, both change mechanisms are equally active - both external and internal variety must be created. New development strategies are required here, in which future markets and new technologies must be taken into account. Possible approaches could be the generic product development process by Ulrich et al. (2020) or Cooper's Stage Gate Process (Cooper, 2022). And also approaches that consider relevant stakeholders such as suppliers and partners (Boer and Boer, 2014; Mikkola, 2006), open innovation approaches (Chesbrough and Appleyard, 2007) or user- and customer-centered approaches, including design thinking (Kwon et al, 2021). To this end, a product structure created with an initial DfV according to Küchenhof and Krause (2019) can serve as the basis for modular structures in different product life phases and from different perspectives.

**No External Change**

The situation where there are no external and internal changes has already been described as the first diagonal case (00). Furthermore, we hold on to external variety without change (left column) - the market offering should therefore not change - and move on along the other internal change mechanisms. An *Expansion/ Contraction* of internal variety could mean that some existing development shares are replaced by new solutions without changing the product range (01). Again, incorporating, services, individual/ customized or digital shares are possible solutions for changing components and internal processes. A reduction of internal complexity *(Contraction)* with product development methods such as the Integrated PKT-approach or Structural Complexity Management are also possible (Krause and Gebhardt, 2023; Lindemann et al., 2010). Internal variety could also be shifted in order to serve the existing market with new partial solutions while core functionalities are retained (02). Methods based on analogies can help find new solutions for known problems (Kalogerakis et al., 2010). The third way is a completely new development that replaces an existing internal variety (03) without generating new product variants.

**No Internal Change**

The bottom row shows a change in external variety without touching the internal variety. In the case of *Expansion*, this means that the market segment already served needs to be further developed (10). This could be done, for example, by a new combination of already developed components and modules, so that the internal variety does not increase but new product variants can be achieved by new combinations. A *Shift* means that a different market segment or market is to be addressed (20). Here, the same components, technologies and processes are used as for the market segment already served. A modular architecture that allows changes within defined interfaces and offers the possibility of mixing and matching components and modules can be used as a strategic tool to enable greater product variety with little effort (Sanchez, 1996). *Creation* means that a previously untapped market is to be developed or created with solutions already provided internally (30), possibly also through a mix-and-match strategy. To be successful, a strong market development strategy is presumably also required.

**Off-Diagonal Rest**

This leaves six off-diagonal entries. Firstly, there is the expansion of an existing external variety through a *Shift* in internal variety (12). Already developed technologies and components are adapted with new shares in order to expand the product range in an already served market segment. The development of completely new components and processes to expand external variety is costly, but also possible (13). The latter could be a solution to completely replace an outdated technology.

A *Shift* in external variety to a new market segment or market can be achieved by extending the internal variety. It may be sufficient to expand the internal variety by adding individual or digital components or services (21). In order to address a new market segment, a new internal variety could also be developed (23). In this case, synergy potential can only be exploited within the market segments, but not in product development since new product structure need to be created.

Two cases remain. The creation of new markets. Either by an *Expansion* of an existing internal variety (31) or by adapting an existing internal variety through a *Shift* (32). The main challenge here is to define a new problem or recognize demand structures in order to create a new market. The question is then what needs to change internally. How can the components be combined and what needs to be adapted to meet the new demand? With a relocation, there is greater freedom of design, but the core functionalities may have to be retained in order to develop a meaningful business model.

### 3.2 Strategical Implications on Product Family Design

The different situations resulting in Figure 4 show possibilities to combine external and internal change mechanisms in different ways. The change scenarios (00-33) are now mapped to the PFIM in order to classify the previously derived development strategies. The result is shown in Figure 5.

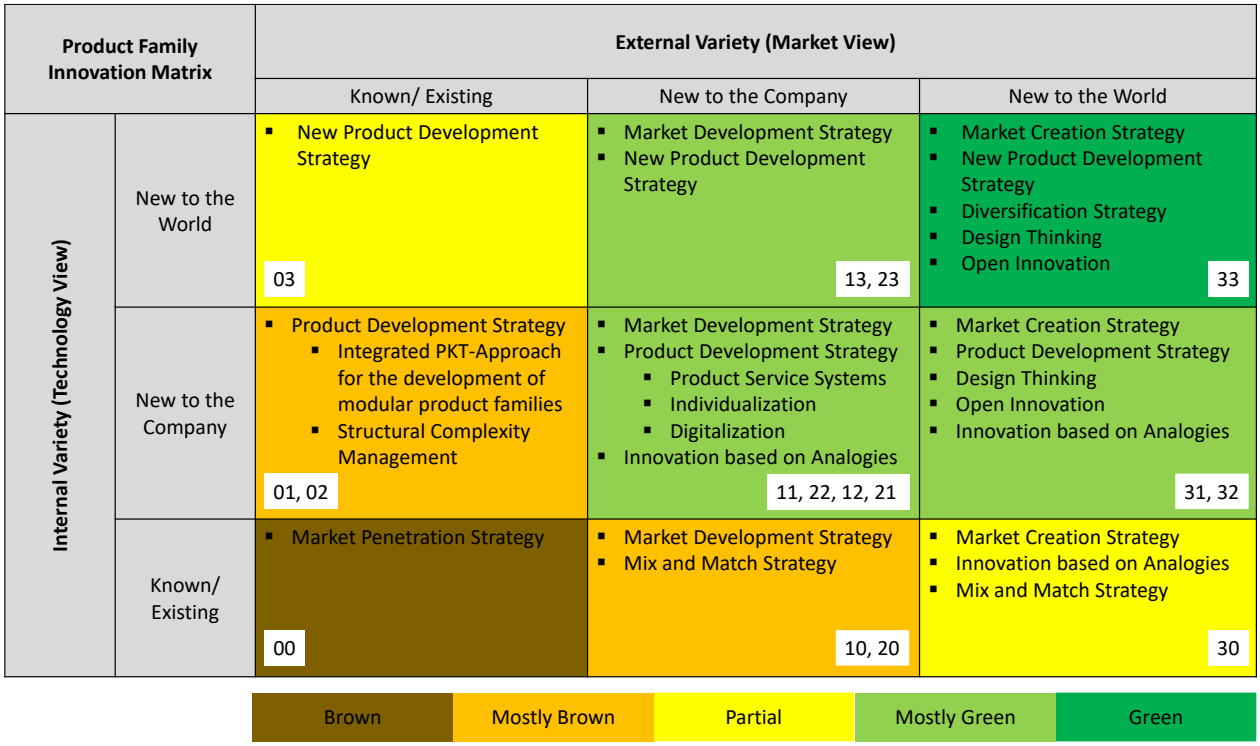


Figure 5. Strategical implications within the Product Family Innovation Matrix

**Brown**

The lower left-hand sector is the area in which the fewest innovations are to be expected. If an existing external variety is to continue to be offered with an existing internal variety without a change being intended, a market penetration strategy can be applied (00).

**Mostly Brown**

The cases where one dimension is NTC while the other is known are categorized as mostly brown, since the innovation potential is rather low.

When realizing a NTC external variety a market development strategy may be applied. By recombining existing components and modules using a mix-and-match strategy, the internal variety can remain the same. A distinction must be made as to whether it concerns the same market segment (10) or a different market or market segment (20).

A NTC internal variety can be achieved through a product development strategy, e. g. by applying complexity-reducing approaches such as the Integrated PKT-approach or Structural Complexity Management. Due to the adaptability of modular products, new parts can also be added (01) or existing parts can be replaced (02). When integrating NTC technological knowledge, the involvement of experts in the respective field can be helpful and useful.

**Partial**

The two peripheral cases in which one dimension is retained while the other is NTW are referred to as partial.
In (30) a new market is to be created, e. g. by finding transfer markets via analogies. The external variety can be expanded by mixing and matching existing components and modules without compromising the internal variety. It is unlikely that this will work for NTW markets and is due to the idealized view of this consideration.
The other extreme is a completely new development for an existing product range (03) through a new product development strategy. This is a very expensive strategy and probably also a purely theoretical construct, as there is no recognizable added value on the market side.

**Mostly Green**

The fields where NTC and NTW shares mix are probably the most difficult to distinguish. These areas are described as "mostly green", as a large proportion of novelty, on the market or technology side, is to be expected here and the innovation potential is therefore also greater. In the middle, external and internal NTC shares meet. Depending on the case, the portfolio can be expanded in an existing market or extended to other markets. Either way, a market development strategy should be considered. For the development of internal variety, individualization, digitalization or offering product-service

systems can be suitable ways to serve new business models (11, 12, 21, 22). Innovations based on analogies could be identified here on the market or technology side.

If NTC markets are to be reached with NTW technology (13, 23), a market development strategy should be used. New product development methods can be used to replace internal variety. If a new market is to be created (31, 32), more attention should be paid to problems, needs and requirements. Therefore, open innovation approaches and a more user-centered process such as design thinking are considered suitable (31, 32).

**Green**

The case at the top right is probably the area with the highest innovation potential. An attempt is made to achieve NTW products with NTW components and processes (33). The aim here is to create both markets and technologies, so a market creation strategy and a new product development strategy are proposed. According to Ansoff, a diversification strategy can be applied that is also associated with a high degree of uncertainty and risk. Companies operating in this area are most likely to take on a pioneering role. Different factors play a role depending on the degree of novelty of the external or internal variety. In new and fast-growing markets, there may be as yet unknown restrictions due to regulations, national and regional directives, etc. For new technologies and concepts, issues such as patents, certifications, liability, etc. must be considered, which can represent enormous cost and complexity drivers. Collaboration with others in the sense of open innovation can therefore be useful. More human-centered approaches such as design thinking could also be suitable for integrating more stakeholders.

### 3.3 Assessment and Support of the Innovation Potential of Modular Product Families

The strategic implications within the PFIM in Figure 5 are intended to answer RQ2 and provide the strategic assessment for the development of modular product families. The brown areas are considered to have the lowest innovation potential. The mostly brown and partial areas run along an axis in the domains of external and internal variety. While some innovative attributes are likely to occur in this area, the combination of external and internal factors is seen as more promising for the development of truly innovative products. Therefore, the mostly green areas have a higher innovation potential. The theoretically highest innovation potential lies in the green area with NTW products and NTW technologies. However, everything there is unknown and fuzzy, as there must be limited knowledge about these areas. Since there is always something existing in the "mostly green" fields, either products or processes, the risk is somewhat lower and the probability of success higher than in the completely green field. Also, approaches that are located in this area are probably more usable for existing companies.

In order to plan innovation projects for modular product families, the PFIM can initially be used as a classification guide. Figure 5 classifies various strategic approaches that are suitable for implementation and can be applied accordingly within the respective fields. To clarify more precisely how the external and internal variety can or should be changed, the matrix of combinations of change mechanisms from Figure 4 can be used.

## 4 Conclusion and Outlook

In this contribution, various concepts and dimensions of innovation in relation to product development were presented. There is great potential for synthesizing these approaches, particularly in the development of modular product families, as there is insufficient methodological support for the development of innovative modular product families. Based on the dimensions of external and internal variety, the PFIM was developed, which represents a classification aid for the development of innovative product families in terms of their innovation potential. By taking into account different change mechanisms, external and internal variety are systematically compared and linked in the PFIM, resulting in a strategic support tool for the development of new modular product families. Innovation approaches from the literature were then assigned to the PFIM. The selection and classification of innovation approaches in this paper does not claim to be exhaustive. In the future, further approaches can be assigned to the PFIM in order to provide a more detailed basis for decision support towards a suitable innovation strategy.

For further research activities, is also interesting to classify development projects already completed in the PFIM and to look at how external and internal variety have changed and which development strategies have been used. Last but not least, the PFIM should provide strategic support for new projects, which is why its use in the project planning of modular product families is desirable.

## References

Blessing, L.T.M., Chakrabarti, A., 2009. DRM, a Design Research Methodology. Springer London, London. https://doi.org/10.1007/978-1-84882-587-1

Boer, Henrike, Boer, Harry, 2019. Design-for-variety and operational performance: The mediating role of internal, supplier and customer integration. JMTM 30, 438–461. https://doi.org/10.1108/JMTM-03-2018-0065

Chesbrough, H.W., Appleyard, M.M., 2007. Open Innovation and Strategy. California Management Review 50, 57–76. https://doi.org/10.2307/41166416
Cooper, R.G., 2022. The 5-th Generation Stage-Gate Idea-to-Launch Process. IEEE Eng. Manag. Rev. 50, 43–55. https://doi.org/10.1109/EMR.2022.3222937
Ehrlenspiel, K., Meerkamm, H., 2013. Integrierte Produktentwicklung Denkabläufe, Methodeneinsatz, Zusammenarbeit. Hanser, München.
Enkel, E., Bogers, M., Chesbrough, H., 2020. Exploring open innovation in the digital age: A maturity model and future research directions. R&D Management 50, 161–168. https://doi.org/10.1111/radm.12397
Henderson, R.M., Clark, K.B., 1990. Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms. Administrative Science Quarterly 35, 9. https://doi.org/10.2307/2393549
Herstatt, C., Verworn, B. (Eds.), 2007. Management der frühen Innovationsphasen: Grundlagen - Methoden - Neue Ansätze, 2., überarb. und erw. Aufl. ed. Gabler, Wiesbaden.
Kalogerakis, K., Lüthje, C., Herstatt, C., 2010. Developing Innovations Based on Analogies: Experience from Design and Engineering Consultants. Journal of Product Innovation Management 27, 418–436. https://doi.org/10.1111/j.1540-5885.2010.00725.x
Krause, D., Gebhardt, N., 2023. Methodical Development of Modular Product Families: Developing High Product Diversity in a Manageable Way. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-65680-8
Küchenhof, J., Berschik, M.C., Heyden, E., Krause, D., 2022. Methodical Support for the New Development of Cyber-Physical Product Families. Presented at the ICED 2022, p. 10. https://doi.org/10.1017/pds.2022.51
Küchenhof, J., Krause, D., 2020. Initial Integral Product and Assembly Structuring – A Case Study. Proc. Des. Soc.: Des. Conf. 1, 2305–2314. https://doi.org/10.1017/dsd.2020.88
Küchenhof, J., Krause, D., 2019. Entwicklung eines Produktarchitekturmodells zur Ableitung modularer Produktstrukturen, in: DFX 2019: Proceedings of the 30th Symposium Design for X, 18-19 September 2019, Jesteburg, Germany. Presented at the 30th Symposium Design for X, The Design Society. https://doi.org/10.35199/dfx2019.3
Kwon, J., Choi, Y., Hwang, Y., 2021. Enterprise Design Thinking: An Investigation on User-Centered Design Processes in Large Corporations. Designs 5, 43. https://doi.org/10.3390/designs5030043
Lindemann, U., Maurer, M., Braun, T., 2009. Structural complexity management: an approach for the field of product design. Springer, Berlin.
Lynn, G.S., Akgün, A.E., 1998. Innovation Strategies Under Uncertainty: A Contingency Approach for New Product Development. Engineering Management Journal 10, 11–18. https://doi.org/10.1080/10429247.1998.11414991
Marzi, G., Ciampi, F., Dalli, D., Dabic, M., 2021. New Product Development During the Last Ten Years: The Ongoing Debate and Future Avenues. IEEE Trans. Eng. Manage. 68, 330–344. https://doi.org/10.1109/TEM.2020.2997386
Mertens, K.G., Rennpferdt, C., Greve, E., Krause, D., Meyer, M., 2022. Reviewing the intellectual structure of product modularization: Toward a common view and future research agenda. J of Product Innov Manag jpim.12642. https://doi.org/10.1111/jpim.12642
Mikkola, J.H., 2006. Capturing the Degree of Modularity Embedded in Product Architectures 19.
Pakkanen, J., Juuti, T., Lehtonen, T., 2016. Brownfield Process: A method for modular product family development aiming for product configuration. Design Studies 45, 210–241. https://doi.org/10.1016/j.destud.2016.04.004
Rennpferdt, C., Zuefle, M., Bagusat, M., Bender, D., Krause, D., 2023. Development of Modular Architectures for Product–Service Systems. Sustainability 15, 14001. https://doi.org/10.3390/su151814001
Salvador, F., 2007. Toward a Product System Modularity Construct: Literature Review and Reconceptualization. IEEE Trans. Eng. Manage. 54, 219–240. https://doi.org/10.1109/TEM.2007.893996
Sanchez, R., 1996. Strategic product creation: Managing new interactions of technology, markets, and organizations. European Management Journal 14, 121–138. https://doi.org/10.1016/0263-2373(95)00056-9
Sankowski, O., Küchenhof, J., Dambietz, F.M., Züfle, M., Wallisch, A., Krause, D., Paetzold, K., 2021. Challenges in early phase of product family development processes. Procedia CIRP 100, 840–845. https://doi.org/10.1016/j.procir.2021.05.034
Ulrich, K., 1995. The role of product architecture in the manufacturing firm. Research Policy 24, 419–440. https://doi.org/10.1016/0048-7333(94)00775-3
Ulrich, K.T., Eppinger, S.D., Yang, M.C., 2020. Product design and development, Seventh edition. ed. McGraw-Hill Education, New York, NY.
Verein Deutscher Ingenieure, 2021: VDI-Guideline 2206 - Development of mechatronic and cyber-physical systems. VDI. Düsseldorf. Beuth Verlag GmbH.
Verein Deutscher Ingenieure, 1993. VDI-Guideline 2221 – Design of technical products and systems - Model of product design.
Vogt, J., Woeller, L.-N., Krause, D., 2024. Effects of Product Personalization: Considering Personalizability in the Product Architecture of Modular Product Families. Journal of Mechanical Design 146, 041402. https://doi.org/10.1115/1.4063825
Xiao, Y., Zhang, H., 2021. New product advantage infused by modularity: Do resources make a difference? J. Prod. Innov. Manag. 38, 473–493. https://doi.org/10.1111/jpim.12590
Zuefle, M., Küchenhof, J., Hanna, M., Krause, D., 2022. Assessing the influence of digital innovations on the organizational design of product family generations 10.

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