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Challenges in early phase of product family development processes

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Abstract

The early phase of product development is often described as particularly challenging. Especially in the case of innovations, various challenges that can be attributed to volatility, uncertainty, complexity and ambiguity (VUCA) are said to come into play. Far more often than breakthrough innovation projects, however, product development projects found in industrial practice incorporate incremental innovations on component or module level. This is especially the case for product developments within product families, where often a large part of modules and technical solutions are used in several products simultaneously and over several development cycles. The aim of this paper is to identify specific challenges especially in the context of the early phase of product families, to assign them to the four dimensions of VUCA and to put them in the context of different boundary conditions, such as novelty degree. For this purpose, a two-part approach was chosen: first, empirical studies concerning the early phase of the product (family) development are summarized, second, three explorative and semi-structured interviews were conducted. As a result, it can be concluded that challenges related to complexity, such as difficult decision-making in balancing internal and external goals or due to interdisciplinary cooperation and coordination between the partners involved, ambiguity, such as due to different interpretations of the same information, as well as uncertainty, such as not knowing about future customer requests, are of particular importance. Challenges related to volatility, on the other hand, were mentioned only sporadically. Furthermore, closeness to the customer, for example, seems to be a boundary condition that favours or prevents the occurrence of certain challenges in the early phase of product family development.

Keywords: Product Architecture Design; Fuzzy Front End; VUCA; Interview

1. Introduction

Regarding product development processes, the difficulties and challenges in the early stages of the development processes are often highlighted. Here, one means the number of options for actions as well as ideas and directions in which the development can go, as long as the product is not yet clearly defined. The steps and tasks of the early phase are defined differently depending on the process model used, but at least include some kind of information gathering, the definition of initial requirements and a first conceptualization. The early phase is often referred to as the “Fuzzy Front End” because of its vagueness [1, 2]. VUCA or individual aspects of it are also often mentioned as being the reason for even more challenging development processes. VUCA refers to the volatility (high speed of change), uncertainty (lack of knowledge about future events and changes), complexity (high number of relations and interdependencies between nodes in a system) and ambiguity (lack of clarity about a situation despite the existence of information or precisely because of a multitude of information) of markets, processes and systems as well as the information and changes therein [3]. Especially in the case of innovation projects these problems seem to lead to the front end becoming "fuzzy". While "fuzzy front end" has almost twelve thousand hits on Google Scholar, only less than ten percent does not refer to "innovation". Accordingly, a high degree of innovation would thus be the main driver of fuzziness in the early phase.

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Product innovation is defined by the novelty of the product, service or system and an implementation in the market [4]. Regarding novelty in design, Pahl and Beitz [5] distinguish between original designs, adaptive designs and variant designs. Original designs incorporate new solution principles, i.e. a new combination of known principles and technologies or the invention of a completely new technology, to solve new tasks or problems. Adaptive designs retain known and established solution principles and only adapt the embodiment to changing requirements. In variant designs, changes in size or the arrangement of parts and assemblies are limited to previously designed product structures. However, hardly any of the products developed today come under the definition of original designs or can be classified as new developments or even radical innovations [6]. This is because reliable solutions for individual functions are carried over often over several product development cycles. In this way, development risks and efforts can be kept as low as possible and development cycles can still be kept short. This is particularly the case for product families, where entire modules as well as product platforms can be reused both in several products at once and across product generations. In fact, single standalone products are quite rare, most are part of a family of products [7]. Product family development thus represents the most common case in industrial practice and at the same time is not always dominated by novelty in design. In conclusion, one is tempted to say that product family development processes are rarely affected by fuzziness or severe VUCA challenges due to the mostly low degree of innovation. Here, we argue that innovation or novelty is only one of several factors, such as closeness to the customer and modularization degree, that influence the emergence of fuzziness or VUCA in the early phase. The aim of this work is therefore to identify challenges in the early phase of product family development, to classify them in the different dimensions of VUCA and to put them in the context of different boundary conditions. This paper takes the first step towards understanding the front-end of a product family development process as well as collecting possible constraints, boundary conditions and influencing factors in it, and thus a first step towards obtaining a more explicit and context-specific process description of the early phase.

2. Process Models for Product Family Development

Looking on what different process models actually say about the development of product families, we find that although they are the most common case, they are rarely addressed. The Stage-Gate process, for example, names the individual steps of the fuzzy front end - ideation, scoping the project, defining the product, and building the business case - but is too superordinate in overall terms to go into details or special features of the process [1]. The product planning process according to Pahl and Beitz [5] consists of seven steps and ends, depending on the definition, with the development order or the list of requirements. The early phase as well as individual tasks and steps are thus described here in detail and can be used for procedural planning. The focus here is very much on an original design, which results from market requirements. However, real-world projects often place strong limitations coming from existing product platforms and due to legislative requirements, which are not considered here.

In the models of product generation development [6], a stronger focus is placed on already existing knowledge as well as on existing solutions and platforms from previous development projects, also called reference systems [8]. Above all, the potential that arises from the reuse of the knowledge base is emphasized here. However, a detailed development process for product families cannot yet be derived.

Krause and Gebhardt [9] follow a variety-oriented approach in planning and developing modular product families. The main aim is to reduce internal variance and variety-induced complexity in the development of variant modules. Although the variety of products and the entire product program should be foresightedly planned in the early phase according to them, they do not explain how this should be done.

Probably the most comprehensive description of a development process for product families can be found in Otto et al. [7]. The authors have sorted methods for product family development and analysis into 13 general steps, some of which probably are not regularly found in industrial practice, and thus created a process instruction. The 13 steps do not represent the entire development process, but only those necessary for developing the product architecture; the process model thus ends before the detailed design phase begins. Interestingly, they also say that performing the various steps is related to the particular case and the constraints and dependencies therein. Furthermore, it is repeatedly emphasised that products within product families are not developed in isolation and that product architectures change over time. However, they do not explain how knowledge, especially in the form of already existing architectures, platforms and modules, is incorporated into the development and to what extent the degree of novelty of the product or product family to be developed influences the development process and thus its fuzziness.

3. Methodological Approach

Based on the findings from the current state of research, we derive two research questions that shall be addressed in this paper.

- RQ1: What specific challenges arise in the early phase of product (family) development?
- RQ2: Which aspects of VUCA can these challenges be assigned to?

The research questions are guided by the hypothesis we derived from the state of the research.

- H1: The occurrence of particular challenges is dependent on certain boundary conditions or targets in the development process.

To answer the questions, we use a two-part approach. Firstly, further experiences from empirical research on industrial practice are gathered and their particular challenges collected. In order not to narrow down the set of results too much, not only research papers that present results from empirical studies specifically on the early phase or in the context of product family development are considered for this, but also those that do not specifically make such a limitation.

Challenges found will be further assigned into the four aspects of VUCA, if possible. The summary can be found in section 4.

Secondly, three semi-structured interviews were conducted with representatives from industry and research. These were people who have both carried out significant tasks in the design of product architectures within industrial projects and who themselves conduct or have conducted research in the area of product architecture design. This gave them a sharper view of the process and its challenges.

The interviews were structured in three parts. First, the interviewees were asked to select a development project from the past as the object of study for the interviews and classify it on the basis of three different boundary conditions using matching scales. These are the degree of novelty, the degree of modularization and the closeness to the customer or end user. In the second part, they were asked to describe the first steps in the development process of that project until the conceptual design of the product architecture was fixed. Finally, interviewees were asked to report on the challenges that have occurred in the early phase of the specific case in general and also explicitly for the different VUCA challenges. If necessary, the reported challenges were in turn sorted into the four aspects of VUCA and discussed with the interview partners. In this context the coherence of the occurred challenges to the boundary conditions mentioned in the first part were also discussed to get a deeper understanding of possible causalities. Results are summarized in section 5.

4. Literature Review on Challenges in Industrial Practice

Not many studies could be identified that explicitly consider challenges in the context of product family development or of product architecture design in the early phase. Liebel et al. [10] describe the challenge of handling requirements dept, referring to components that were developed in an earlier development process with different requirements and are now to be reused as a carry-over module in the current product design. Within an industrial case study, Haug et al. [11] address the challenge of selecting appropriate modules or functions for a product family. They also refer to context-specific or subliminal decision criteria. For example, it might be advantageous to offer a certain solution, even though it is rarely requested and hardly yields any profit, if, for example, an important major customer expects it. Gepp et al. [12] have collected literature and studies on modularisation projects in engineer-to-order (ETO) companies and also identified challenges. In modular design, compromises must not only be found between the requirements of different customers, but must also be harmonised with the goals of the company. After all, the resulting product architectures can also have an impact on the organisational structure of the company. All sources from this collection have thus addressed challenges in *decision-making*. As these are due to conflicting, multiple and subliminal target criteria, this challenge can be titled a COMPLEXITY challenge.

Far more reports on challenges can be found on the keywords “requirements gathering”, “requirements definition” and also “requirements management”. However, these also represent the core activities of the early phase of any product development process, regardless of the type of project or product. It should also be noted that various authors also talk about complexity, complex projects or complex products in this context, without explaining exactly what they mean by this.

According to Lowe et al. [13], engineers spend 35% of their time searching for and interpreting information. Zhang et al. [14] also note that engineers spend a lot of time specifying customer requirements and iteratively translating volatile needs into defined solutions. This is not limited to the early phase, as requirements and solutions emerge in co-evolution, i.e. requirements become increasingly concrete and multiply as design decisions are made [15, 16]. Overall, the interpretation of information into technical requirements, also called *transformation*, seems to be a challenging process. Karlsson et al. [17] reported that some of the requirements were not elicited but invented by designers. According to Cooper et al. [18], conflicting requirements can arise from different interpretations of the same information by different members of the design team. Problems with incorrectly or imprecisely transformed information or different interpretations of the same information are also documented by [14, 19, 20]. The problems in translating information into requirements addressed in this collection of sources can be classified as challenges of UNCERTAINTY or AMBIGUITY, depending on the cause, whereby problems with different interpretations in this context are a strong indication for AMBIGUITY.

Communication problems in various forms are mentioned both externally to customers or stakeholders [19, 21] and internally between individual project members [10,17, 19, 22]. According to that, customers could not properly put their problems into words, but formulate solutions that they think they need [10]. *Internal communication problems* are often described as insufficient interdisciplinary cooperation, insufficient exchange or even unclear boundaries in authority and responsibilities [10, 19]. Thus, problems in communication are strongly related to the COMPLEXITY of the development process and to the diversity and interconnectedness of the people involved in it.

Further evidence of COMPLEXITY can be found in [16, 17, 23], who, similar to [12], identify challenges in *prioritising requirements* or in finding trade-offs between different goals.

Finally, there are also sources in this pool that explicitly talk about COMPLEXITY and the increasing number of system elements as well as relations and dependencies between them. Requirements thus also arise from and multiply with the relations between system elements [24] or due to emerging potentials in platform design [22]. Difficulties in understanding and *recognising dependencies and relationships* between different requirements are mentioned by [10, 17, 20, 23]. Other difficulties that can be generally summarised as *documentation problems* in context of complexity are described by [10, 16, 19, 20, 21].

The last pool of sources contains studies on industrial practice in general. Eisenmann and Matthiesen [25] identified *decision-making* among a multitude of objectives as a challenging non-routine activity, including the *prioritisation of requirements* and the selection of solutions for conflicting requirements, due to COMPLEXITY. Daalhuizen et al. [26] state that UNCERTAINTY results from a *lack of understanding* of the task, from its complexity, or from insufficient *information* *exchange* between the people involved. However, it is not clear whether the cause lies more in a lack of information or in a lack of understanding of it or in its AMBIGUITY, or in both. In contrast, further findings by [25] give a stronger indication of ambiguity. They found that a lack of information was rarely a problem, but insufficient information presentation very much was. Table 1 summarises the explicit challenges found and shows which aspects of VUCA they can be traced back to.

Table 1. Summary of the challenges found in literature.

Challenges in …	Traceable to	References
decision-making in requirements definition	complexity	[10, 11, 12, 25]
internal communication	complexity	[10, 17, 19, 22, 26]
prioritising requirements	complexity	[16, 17, 23, 25]
understanding dependencies & relationships between requirements	complexity	[10, 17, 20, 23]
documentation in general	complexity	[10, 16, 19, 20, 21]
transformation of information into requirements	uncertainty or ambiguity	[13, 14, 15, 16, 17, 18, 19, 20]
understanding of information	uncertainty or ambiguity	[25, 26]

5. Experiences from Industrial Practice

The three cases, which are summarised in figure 1 based on their boundary conditions, come from three different German medium-sized to large companies. Interview partners were asked to choose one ongoing or already completed project for the interview, for which they have a good overview as well as insight into its early phase. In case 1, market maturity has already been accomplished, in case 2 and 3 the project is still ongoing. The cases are sorted according to three boundary conditions, whereby the positioning of the markers was done by the respective interview partner.

At first, is the degree of novelty of the product architecture (figure 1), i.e. the number of changes compared to the previous generation. It thus relates to the classification of originality of the design by Pahl and Beitz [5] (see definitions for original design, adaptive design and variant design) from the company's perspective. In all three projects there are major changes and upheavals between the generations. In case 3, only minor changes were planned at the beginning, but due to change propagation, several modules were affected in the end. However, the internally perceived degree of novelty should not be confused with the degree of innovation. As case 2 and 3 have not yet reached market maturity, it was not possible to assess the degree of innovation. In these two cases, however, there are still potentials and plans for achieving a higher degree of innovation.

Second is the degree of modularisation (figure 1); it means how strongly the product architecture is defined or, vice versa, how many individual degrees of freedom are available for each variant or customer order. In the field of plant engineering, for example, there are companies whose products are all based on a common knowledge base or core technology, but are otherwise developed completely individually and customized for the respective customer order. In contrast to that, the superordinate product family in case 3 is almost completely defined; customer-specific variants are scarce. In case 2, the definition of the product family is not yet completely defined and contains a high customer-specific share, though the aim is to limit this in the course of further development. This intention is marked with an arrow in figure 1.

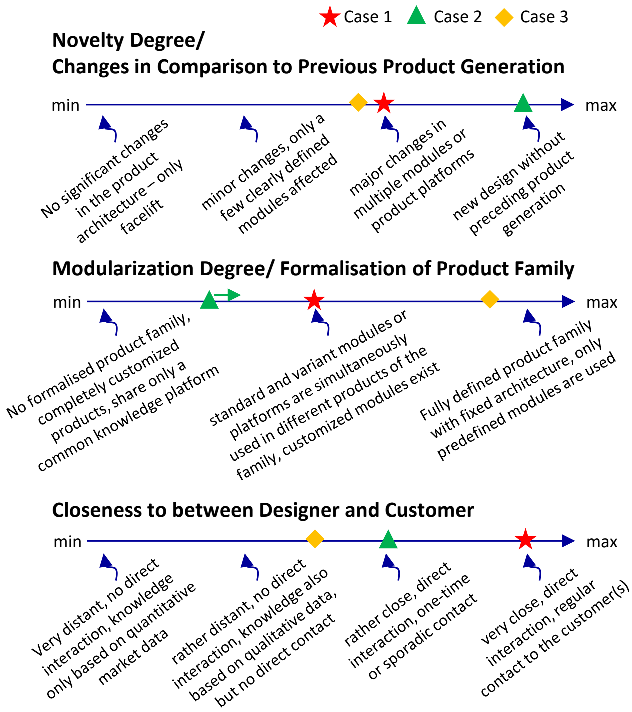

Fig. 1. Boundary conditions of the examined development processes

The last boundary condition we want to classify is the closeness of the designer to the customer (figure 1). This includes both the immediacy of the interaction as well as its frequency. All three companies operate in the business-to-business segment. In case 1, there is a very close exchange between the person(s) who define the product architecture and those who order it. Although there is direct contact between company representatives and clients in case 3, these company representatives are not part of the early development phase, i.e. they are neither involved in the definition of technical requirements nor in the product architecture, but are only involved in the later stages for evaluation.

The second part of the discussions focused on the particular development process in the early phase. However, due to their level of detail and specialisation, these can hardly be arranged or compared with each other. Although general activities and steps, e.g. information gathering, requirements translation or the mapping of functions in the architecture, can be found in different variations in each case, bringing these down to a common thread for all three cases would not have any added value compared to the process models already generally defined in the state of research [e.g. 5, 7]. However, it can be seen that the specific process is highly dependent on the chosen design approach. This can influence both the particular sequence of the individual generic task steps, their intensity as well as eventual iterations. Further dependencies could exist on the degree of novelty of the product architecture. Indications of this were expressed in the interview on case 2, in which there was no reference system within the company in advance.

Finally, the interviewees were asked about the specific challenges encountered in the case under consideration. All three named COMPLEXITY as the main challenge, e.g. in the *decision-making process* of the early phase, i.e. balancing internal and external goals. They wanted to implement all customer wishes (external objective) at the best possible price, but without creating too many individual or variant solutions that might have an impact on the entire architecture (internal objective) and thus at the same time increase internal complexity and costs for both the company and the customer. Here, complexity seems to be further driven by the degree of formalisation of the product family or the quantity of interlinked system elements. This challenge also coincides with the results from the literature study. In cases 2 and 3, teamwork was also named as a complexity driver. *Interdisciplinary cooperation and coordination* between the partners involved would be difficult to manage and would become more difficult with an increasing number of people or disciplines involved or the degree of task distribution. We did not explicitly record these boundary conditions during the interviews. However, indications that there is a connection can also be found in the results from the literature (see table 1).

AMBIGUITY was emphasised in case 3 in the form of *different interpretations* of the same requirements and resulting communication problems between persons involved. The interview partner mentioned here also the barrier between the designers and the customers. Differences in interpretation would always arise in the team and would then have to be reconciled. In contrast, problems in the interpretation or transformation of customer requirements were denied in case 1. There would be discrepancies in the requirements definition, but these would not primarily result from ignorance on the customer side, lack of understanding on the developer side or misunderstandings between both sides. The reason for this is rather the intentional withholding of information about the prioritisation of goals in order to keep negotiating leeway large. With regard to ambiguity, there is hence a clear connection to the immediacy of the exchange between designer and customer and possibly also to the interdisciplinary composition or size of the design teams.

UNCERTAINTY about future changes on the market side, in this case changing customer demands, were particularly emphasised in case 2. Here, the lack of information and previous experience with the new product architecture was particularly emphasized by the interviewee. In the other two cases, market-side changes related to competitors or customer preferences were not denied, but were classified as a rather secondary problem or risk.

VOLATILITY as a constant and independent challenge was hardly mentioned by the interviewees. This was only named in case 2 in the form of a changing team composition and the associated new or changing distribution of tasks. However, it is unclear whether this is related to the actual development process and its boundary conditions, such as the degree of novelty, or whether it is just a random occurrence.

6. Discussion

The apparently subordinate importance of volatility in the initial phase is rather surprising. This is not in line with the general state of research. Presumably, however, this can be attributed to the definition of volatility and the difficult demarcation from the concept of uncertainty. Thus, high volatility in the market is more likely to be perceived as uncertainty in the early phase. In turn, unpredictable changes usually emerge later in the process. In the literature, volatility was also briefly mentioned by different authors [e.g. 10, 17, 22], but not backed up with concrete challenges from empirics and therefore not included in the list of results.

In comparison, it can be stated that the results from the literature study can also be found to a large extent in the results of the interviews, which increases their overall significance. The fact that not all challenges occur equally, but only in certain contexts, is also in accordance with our hypothesis. However, despite these findings the validity and thus significance of the two-part study is still limited. Overall, only a few reports on the early phase of product family development could be found. The additional integrated literature on early phase development in general, may have been recorded in the context of special cases that do not match our framing within product family development.

The interviews and their findings also contain a certain validity due to their explorative nature, but are only comparable to a limited extent due to the different boundary conditions. It is also possible that the projects were subject to other significant boundary conditions or influencing factors that were not consciously perceived by the interviewees and therefore could not be reported as such. Team composition and its various dimensions is one such example. Other contextual factors could also have an influence here. Collections of relevant factors can be found in [27, 28], for instance. Thus, there is a need for further research here.

7. Conclusion and Outlook

In relation to RQ 1, many different and partly specific challenges for early product (family) development could be collected (see table 1). They show a more diverse picture of the early phase and explain to some extent how exactly fuzziness respectively complexity, ambiguity, uncertainty and volatility manifest themselves in it (RQ 2). Another result is that not all aspects of VUCA seem to be equally relevant for the early phase. This could also be partly attributed to the insufficient definitions of the individual aspects. For example, uncertainty and ambiguity are not always clearly distinguished in the literature; volatility also seems to be mixed with uncertainty in the perception of the developer.

Regarding our hypothesis that the occurrence of the main challenges of VUCA depend on certain boundary conditions, we see rather clear indications from the interviews. The occurrence of ambiguity, for example, seems to correlate with the proximity to the customer, which is also plausible insofar as increased customer or user proximity can also increase the understanding and empathy towards them; thus, making it easier for the designer to interpret customer or user information. Uncertainty in the early phase seems to be related to the novelty of the product architecture. This can be explained by the lack of an internal reference system, the lack of information and experience in the firm and the associated high risk. An interesting finding is that modularisation and interdisciplinarity, or rather their increase, are on the one hand the solution to increasing market, cost, and time pressure, and on the other hand seem to be themselves also a cause and driver of complexity. However, this is only a contradiction at first glance. A high degree of modularisation in the product architecture requires long-term planning of carry-over parts and their maintenance in a wide variety of product families, which in turn are developed and maintained by many different people and accordingly have to meet a large number of different goals and requirements; thus, making the development process more complex again.

As an outlook for further research efforts, on the one hand, the validity of the results could be increased and, on the other hand, further boundary conditions and influencing factors of early product (family) development could be collected and investigated. Another interesting prospect lies in the process description or modelling of the early phase. Here one could investigate the extent to which different projects that have emerged under different conditions can actually be mapped in a general model including the most relevant boundary conditions. As soon as we have clear connections between specific challenges and the boundary conditions in the process, occurring challenges could be tackled with appropriate methodical tools thus become better manageable. The higher goal is thus to apply only those methods that are necessary and appropriate for the case at hand.

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