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A Conceptual Framework of Product Family Architecture

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Abstract
For the description of product family a number of modelling methods exist in literature. These methods describe individual applied research. Thus, they are limited for the practical and singular purposes. Research on the product family development based on theory is emerging. The product family development is related with the product architecture, product family architecture, product platform as well as configurable product. The separate meaning of the product platforms and configurable products are accepted in the literature. Opposite to this, product architecture and product family architecture are often treated as synonyms. In this article differences between product architecture and product family architecture are discussed. The term product architecture should be used when a company wants to redesign individual product because of the certain benefit from one or more phases of life cycle. When commonality and variety should be planned for a related group of products (product variants) the term product family architecture should be used. Our research question is: What is a product family architecture and what are the elements of which product family architecture consists of? Description of product family architecture involves description on three levels: domains concepts, the notation used to define the elements of domains and the design rules. In this article the domains of a product family architecture is explained.

Keywords: product family, product family architecture, product architecture

1 Introduction
Shrinking product life cycles, increasing competition, rapidly changing technologies, and variety in customers' demands describe driving forces for product development process. Manufacturing companies respond with different approaches on those driving forces. One of the approaches is to offer a wider range of product assortments. Design of one-of-a-kind

products requests to repeat all phases of design process every time when the requirements change. As the potential of product family commonality is omitted, the explosions of product assortments lead to high costs in design, production, assembly, maintenance, etc. [15]. Therefore, companies need to design a wider range of product assortments with the less variations in design, production and maintenance between them. With that approach companies are focusing to the development of product family instead to design one-of-a-kind products.

Andreasen *et al.* [3] p.20 defined product family as “a set of products, which are created from a common set of components for obtaining a range of product variants, which are able to cover certain market segments”. Each member of product family is a product variant. The goals of development product family are to show variety, which is interesting for the market; to show the highest possible degree of commonality in relation to the system found in the manufacture and product life cycle; to show the lowest possible complexity in all activities, which relates to product development, manufacture and life cycle activities [16].

Several different models exist for the description of product family in literature. Hegge [7] described the product family based on the generic bill of material. Generic bill of material consists of the components used within the product variants, relations between the components and component’s attributes. Erens [5] extended the generic bill of material with the three structures of a specific domain. Those structures belong to the functional, technology and physical domain. Similarly, Jiao and Tseng [9] suggested representing product family based on the three parallel views: functional, behaviour and structural view. Sivard [17] defined a generic information platform of product family based on the STEP standard (ISO 10303-214). A generic information platform reflects the trace from various requirements to functions and different properties of product components.

In abovementioned examples the models of product family were described the attributes of the products and product structures necessary for the utilization of the configuration process. Hence they do typically not focus on information, which is not directly used to perform the configuration itself. Such approaches describe individual applied research without focus on theoretical research on the product family development.

The product family development is related with the terms product architecture, product family architecture, product platform as well as configurable product. The separate meaning of the terms product platforms and configurable product are accepted in the literature. Opposite to this, product architecture and product family architecture are often equally treated.

Riitahuhta and Andreasen [16] defined architecture as a structure of units of a product and their assembly relations. The units are the elements, which constitute the product when we have performed a restructuring of the product programme regarding market and product life cycle and regarding company internal activities like production and assembly. From the definition it is not clear whether Riitahuhta and Andreasen mean with the term ***architecture*** the architecture of a single product or the architecture of a product family? Moreover, in literature does not exist the clear differences between those two terms. The consequence of the lack of the difference is the ambiguous interpretation of both terms. In the research area of product architecture the most used definition of the product architecture is a scheme by which the functional elements of the product are arranged into physical chunks and by which the chunks interact [21]. The meaning of this definition is in the understanding the classification of the architecture on the integral and modular. Such a classification is made based on the mapping between the functions and physical components.

Lanner and Malmqvist [10] stated that all products have some kind of architecture even if it has not necessarily been considered during the design phase. Similarly, we assume that every product family has some kind of product family architecture. The key to rationale and successful product family design is product family architecture [13].

2 Differences between product architecture and product family architecture

Ulrich and Eppinger [21], p. 168 defined variety as ‘the range of product models the firm can produce within a particular time period in response to market demand’. This definition is oriented on manufacturing capability of company to produce different products. The variety can be seen from the two viewpoints: need for variety and variety implementation (table 1.).

Table 1. Classification of the variety

	Need for variety	*Variety implementation*
Anderson and Pine [1]	External	Internal
Jiao and Tseng [9]	Functional	Technical
Martin and Ishii [11]	Strategic	Tactical

Analyzing the need for variety companies seek for an answer on the question: Why do we need variety? Analyzing the variety implementation companies seek for an answer on the question: How can a variety be realized?
External, functional and strategic varieties are varieties, which define the need for variety. External variety is on the sight of customer. It has two categories: useful and useless variety [1], p. 45. Categorically, customer appreciate useful variety and regard useless variety as not transparent, unimportant or even confusing. Functional variety refers to differentiation in functions between the products from which customers expect different usage or application. Strategic variety decisions are those that affect the number and scope of the variety offered to the customers.

Internal, technical and tactical variety describes the implementation of variety in the company. Internal variety takes the form of excessive and unnecessary variety of parts, features, tools, fixtures, raw material and process. Technical variety refers to diverse in technologies, design methods, manufacturing processes etc. that are necessary to achieve benefits within certain phase of product life cycle. Tactical variety decisions are made at the level of the design engineer and involve decisions that affects the manufacture of the product, but which are not obvious to the customer.

These two classifications of variety are related with different strategy within the company. Focused only on the variety implementation the companies are oriented on the development of single and separate products and expected the reduction effects within a certain phase of product life cycle. When companies are faced with need for variety together with the variety implementation then they are oriented on the development on the product families. During the development of product families it is primary important to define the need for variety between the product variants and secondary is to define the variety implementation. Variety implementation within the product family is important because increasing the need for variety without controlling variety implementation does not guarantee an increase in long run profits

[15], p. 2. Some of the companies have experienced quite the opposite effect: the loss of profits along with the uncontrolled increase of product versions.

The concept of product is ambiguous, when meaning varies according to context. Sometimes the context is design and sometimes to production. In everyday language, concept refers to several individual products of the same kind, to a product family as well as to the variant of the family. Thus, it is important to differentiate what is the actual meaning of a concept. In table 2 two separate concepts, design and product, are related.

Table 2. Product vs. Design

	An single, separate design (1)	**A number of related designs (n)**
Single, separate product (1)	One design for one product (1-1)	Many designs for one product (n-1) ð technical variety
A number of related products (n)	One design for many products (1-n)	The multi-product approach (n-n) ð functional variety

In the first (1-1) case a one-of-a-kind product is usually engineered and made to order. Thus, a product is the result of an *ad hoc* realization project, which is seldom systematic and hardly optimized. In the case (n-1) many diverse, but related designs for one product are developed. In redesign projects alternative revisions are sought after in order to enhance the way a product meets a life-cycle phase. This may enable a transition to the third (1-n) case, where a number of similar products are made to stock with an optimised mass production system. With a multi-product approach (n-n) a number of products are made or assembled to order as variants, i.e. instances of a family. The designs are typically derived with a systematic manner from the generic description of product family. Also the production can be systemized for making a product variant. According to Anderson and Pine [1] a set of transitions between cases (1-1), (1-n), (n-1) and (n-n) signify different manufacturing paradigms.

Based on above-mentioned classification came the need for different purpose of establishing the product architecture and product family architecture. Product architecture is established when exists the need on the market because of which is necessary to implement variety within a company. In addition, product family architecture is established when the group of product variants constitute the product family and when the reduction effects are expected in one or more phases of life cycle. On the following example two approaches will be explained. The example is basic fountain pen as shown in figure 1 (adopted from [6]).

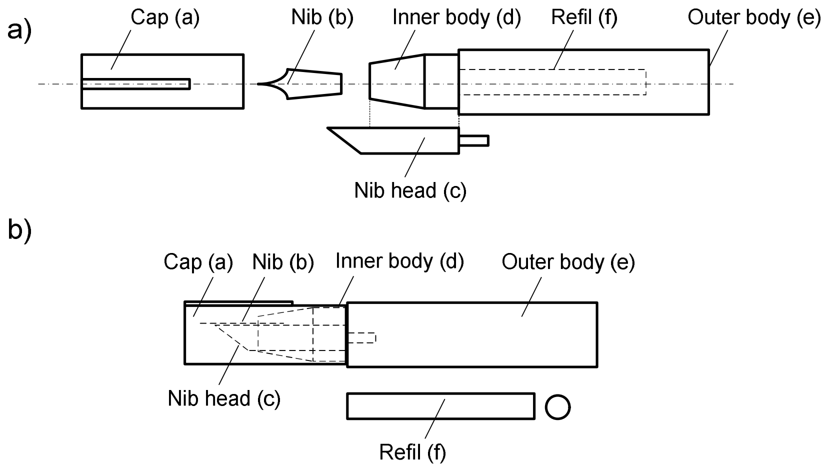

Figure 1. (a) Fountain pen in a disassembled position (b) fountain pen package (without the refill assembled)

First approach considers that company offer on the market an individual product, which is produced by mass production. The assembly sequence is illustrated in figure 2a. It represents assembly process in which parts are assembled one after the other. The product consists only of the parts and subassemblies are nonexistent. When company wants to achieve technical variety in one phase of life cycle (for example in assembly phase) it will have to define new product architecture. New product architecture will consist of two sub-assemblies (bc and de) as shown in Figure 2b.

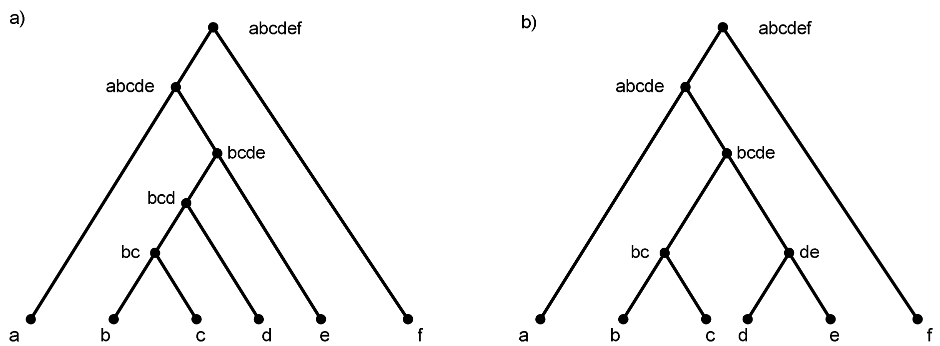

Figure 2. Two possible assembly sequence designs for the pen

These sub-assemblies can be concurrently assembled and because of the time reduction in assembly process the company can benefit from new product architecture. In such a case when company wants to achieve certain benefit from one or more phases of life cycle the term the product architecture should be used.

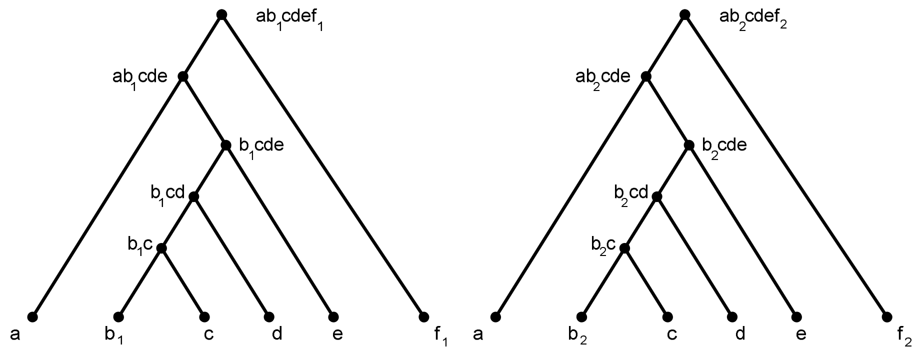

Figure 3. Separate assembly sequences of pen variants

In second approach company offers different pens on the market and differentiation between them is in parts b (b1 and b2) and f (f1 and f2). If these product variants don't belong to product family the assembly process for both variants is separate as shown in figure 3.

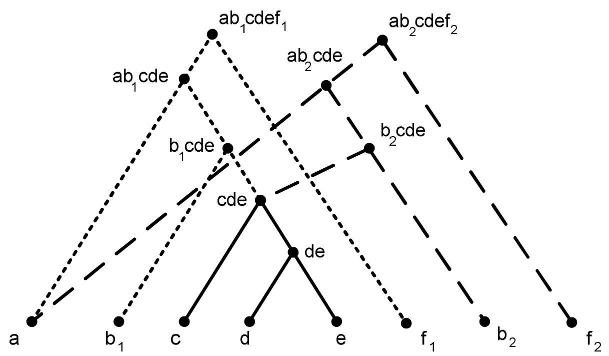

Figure 4. Assembly sequences of pen product family

Because commonality and variety between product variants is not defined product family does not exist. When company wants do establish product family and define commonality and variety between the product variants the product family architecture should be established. The re-defined sub-assembly 'cde' in Figure 4 is a common between product variants. It is assembled independently from the rest of the product.

The conclusion from the example is that term product architecture should be used when company wants to redesign individual product because of the certain benefit from one or more phases of life cycle. When commonality and variety are planned for a group of products (product variants) the term product family architecture should be used. Therefore, the meaning of product architecture and product family architecture is not the same so it should not be equally treated.

3 Product architecture

The product architecture is mostly used in the literature as a schema by which functional elements are arranged into physical units and the way in which these units interact [21]. Based on the arrangement between functional elements and physical elements Ulrich and Eppinger [21] defined classification of product architecture on integral and modular architecture. Table 3 shows the relation between the integral and modular architecture. Integral architecture has one or more functions related to many physical elements. In modular architecture one or more functions are related to one physical element.

Table 3. Modular and integral product architecture

1 : 1	One function is related with one physical element	*Modular architecture*
1 : N	One function is related with many physical element	*Integral architecture*
N : 1	Many functions are related with one physical element	*Modular architecture*
M : N	Many functions are related with many physical elements	*Integral architecture*

However, the definition of the module does not come from the modular architecture as should be expected. Baldwin and Clark [4] define module as a unit whose structural elements are powerfully connected among them and relatively weakly connected to element in other units. As Baldwin and Clark [4], p. 63 concluded '*it is difficult to base a definition of modularity on functions, which are inherently manifold and non-stationary'*. Much more important are relationships among structures and decisions on which such relationships are based. Takeishi and Fujimoto [18] have described modularization in product, modularization in production and modularization in supplier system based on the consideration of different phases of product life cycle. Nonomura *et al.* [19] show on the refrigerator example three different modular structures when different optional actions in the end phase of refrigerator life cycle was considered.

Analyses in chapter 3 showed that considering modular architecture only as a mapping between function and physical units is not broad enough. Modularization should be considered also as a mapping between the design phase and one or more phases of product life cycle. The result of modularization is represented as a modular product architecture, where modularity is an attribute in the context of life cycle. To conclude, it is important to consider the mapping between the design phase and one or more phases of product life cycle when product architecture should be established.

4 Product family architecture

As already mentioned, Lanner and Malmqvist [10] stated that all products have some kind of architecture. The argumentations of that statement should be sought in the definition of the product architecture. Product possesses product architecture if it has functional elements, physical elements and if it is known how functional elements are arranged into the physical elements. Every technical product consists of the physical elements and every physical element realizes one or more functions. So the Lanner's and Malmqvist's statement is true. But is it possible to state that every product family possesses the product family architecture? The answer on that question is negative, because the group of the products consists the product family even they are not necessary designed based on the product family architecture. Additional difference between the product architecture and product family architecture is that product architecture exists in every product even it is not planed during the product development. But product family architecture exists only if it is planed during the development of product family.

The question, which motivated this research, is: What is a product family architecture and what are the elements of which product family architecture consists of? The results, which are expecting from this and further research, should enable to reuse the product family architecture in the description of product families.

In order to handle development of product families it is important to describe how a product family is built up [20]. This phenomenon is named product family architecture (Mortensen *et al.* [20] in his paper called this phenomenon architecture but according to the abovementioned discussion product has an architecture and product family has product family architecture). The product family architecture is thus explaining the building principles for a product family.

The aim of development product family architecture is planning the commonality and variety between the groups of products, which companies offer on the market. Before development of product family the companies already have individual products on the market. They do not develop the product family for new, innovative products. They are two reasons for that. First is the lack of product knowledge. Without the knowledge of product design it is difficult to define a product family. Second, companies have different interest when develop one-of-a-kind separately designed products then product family. From the set of separately designed one-of-a-kind products the companies expect the feedback from the customer before they launch the product family. Therefore the development of product family is a redesign process. The process does not necessary imply the redesign of the components even sometimes it is necessary to redesign some components to achieve the fulfillment of multiple requirements. Mainly the redesign process is composed of the product restructuring with an aim to define the commonality and variety between the groups of products.

The reasons for development of product family architecture are:

- time to market has to be shorter and development of individual product does not achieve the requested time,
- there exists a need for planning commonality and variety between the group of products,
- the effect on the meeting between the product family and its instances and life cycle.

4.1 Conceptual framework of Product family architecture

Description of product family architecture involves description on three levels: domains concepts, the notation used to define the elements of domains and the design rules. Domain concepts describe the domains, which identify with the product family architecture. Each domain relate to the entities of domain and relations between the entities. For precisely relating to the entity the attributes of the entities have to be defined. Domain concepts and notation of the entities are not alone enough for the description of the product family architecture. Description of product family architecture also comprises of design rules. The design rules constrain the use of the product family architecture by defining what kind of relationships is allowed and how the entities are interrelated between the domains concepts. In this article the domains of the product family architecture will be elaborated.

Product assortment model

Product assortment model represents the product family, categories of product variants and product family requirements. Product family consists of the product variants, which are grouped in the product categories. Product categories represent the market segment in which the characteristics of product variant are planned. Product category has sub categories according to certain range of characteristics. Subcategories, categories and product family are related with the hierarchical relationship between them.

Requirements for the description of product family are organized into the requirements category. It represents a set of requirements serving the same purpose and it is organized into the hierarchical relationship. Requirements are defined by the name, description and value.

They represent the structural attributes and quantity attributes of the product family. Product family has overall requirements, which are the same for all product categories. Besides them, some requirements exist only for certain product categories. Those requirements are included in the product categories and are not part of the overall requirements of product family. Some requirements exclude other requirements and some requirements include additional requirements. Requirements with the additional request to the other requirements are interrelated with the operation, which identify the type of relation (include or exclude).

Family function model

Family function model represents the description of the function structure for the whole product family. Function structure of the product family is named Family function structure [24]. It consists of the main function and sub functions. In family function structure exists three types of functions: basic function, special function and auxiliary function [14], p. 435. Basic functions are functions, which are fundamental to all the product variants. Special functions comprise of product variants listed by the customers' requirements. Special functions are complementary and task specific functions that need not appear in all product variants. They are used to define the functional variety between the product variants. Auxiliary functions are implementing when basic functions or special functions need some additional functions to fulfill overall function. Function has a wirk-space and wirk-time [12] p. 103. The word *wirk* doesn't have exact translation in English and it had been suggested not translated it and use it as new terms: "wirk-principle, wirk-movement", etc. [22]. Some of possible suggestions of term *wirk* were: working, active or action [22]. Wirk-space describes the volume in which the function shall be delivered and wirk-time describes the sequence in which the function shall be delivered.

Organ model

Realization of functions requires organs. Organ is defined as an interaction between the several material areas, which based on the laws of physics can create effects [2]. An organ is a structure of wirk elements and it consists of attributes of the wirk elements and attributes of relations between the wirk elements [8], p. 169. A wirk element is a point, line, surface or space of continuous geometry and uniform material [8], p. 132. Wirk element consists of wirk surfaces, which are located on the physical elements. Wirk surfaces in the organs represent the interface between the two physical elements in contact. During the development of product family it is important to clearly determinate and defines the interfaces between the physical elements. Equally important is defining the interaction between the interfaces. In organs one wirk element receives stimuli and other wirk element deliver response. These wirk elements in organs are designated receptors and effectors respectively [12], p. 41. Effects between the receptors and effectors are based on the physical law. Therefore to completely determine and define the interfaces within the product family it is important to define the interfaces and effects between interfaces them or organs.

Module model

One of the characteristics of product family architecture is that consists of the modules. Modules are classified as basic, special and auxiliary modules [14], p. 434. For module's determination it is not sufficient to analyze only the functions. Instead companies expect the benefits from reduction effects in one or more phases of product life cycle. Therefore it is important to define the phases based on which module will be determined and meetings between the modules and phases. For module it is important to define the characteristics of the parts, which are in contact with other parts of different modules or with other systems (human, environment or technical). For these parts surface condition, material, shape and tolerance should be defined. Surface condition determines expected characteristics of the parts resulting form the manufacturing process. The characteristics of surface condition represent the meetings with the production life phase. These characteristics are related with the tactile appearance, visual appearance or surface texture. A tactile appearance is the appearance of a surface of a part regarding the sense of touch. A Visual appearance is the appearance of a surface of a part regarding the optical impression. Surface texture is the characterization of irregularities of the surface. For material characteristics it is important to define the material quality but also environment condition in which module will be used. For some environment condition material can have different characteristics. The shape and the tolerance of the portion of a part, which represents the interface, should be specified.

5 Conclusion

This paper discussed the difference between the product architecture and product family architecture. As it was elaborated these two terms don't have equally meaning and therefore they have to be used separately. Product architecture should be used in relation with one-of-a-kind product and product family architecture with the product family. By defining product family architecture commonality and variety between the product variants is planned. Hence, it is achieved to reuse the elements of product family in design of product variants. The further research is directed to the description of domain's concepts, notations for domain's elements and definition of design rules. The overall aim is to define the product family architecture, which should be possible to reuse for the description of product families.

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