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ABSTRACT

Today's markets are characterized by the need of offering products in view of a variety of rapidly changing customer demands. The concept of modular product families is widely used towards this goal. There are various definitions in the literature capturing different aspects of modularity. These definitions are generally not embedded into the design process. At the same time, a wide range of definitions not always consistent with the literature are used in industry. A framework with the following characteristics is therefore needed: (1) integration of the most widely-used academic definition of modularity, (2) a high degree of structure, and (3) clear support of the design of modular product families. We respond to this need by augmenting Axiomatic Design as a well-established, mathematically rigorous, and structured starting point. First, we formalize and augment the detailing process within Axiomatic Design. Second, we reason on the mapping processes that are part of Axiomatic Design. Third, a broadly used definition of modularity is incorporated into the framework. The utility of the framework is shown by applying the framework at three industrial companies.

1. INTRODUCTION

The economy is moving towards ever increasing product variety [1] and ever decreasing product life cycles [2]. This challenge cannot be answered within the traditional paradigm of mass production as its underlying premises are stable demand and long product life cycles. We need to move into the age of mass customization and provide "variety and individual customization, at prices comparable to standard goods and services" [3]. Pine points out modular product families as one of the five ways of mass-customizing products and services. Customization is accomplished by exchanging, modifying and recombining modules while economies of scope are realized by a unifying structure. The success of modular product families has been shown for various industrial applications such as automotive components [4], printers [5], and power tools [6].

Though widely used, the underlying concept of modular product families, i.e., modularity, has no generally recognized definition used both in industry and academia [7]. We believe that the reason is that in academia the focus is more on what modularity is, whereas in industry it is on what modularity can achieve. That is why our intention is to provide a framework for modular product families that not only (1) *incorporates the most widely used academic definition of modularity*, and (2) *exhibits the structural rigor of an academic definition*, but also (3) *supports the design of modular product families in practice*.

In this paper we provide such a framework. We start by summarizing existing definitions of modularity in academia and industry in Section 2. In Section 3, we present the original Axiomatic Design (AD) as conceived by Suh [8-12] and motivate the augmentations to AD needed for modular product families. In Section 4, we present the framework for modular product families, the core contribution within this paper. This is achieved by augmenting and formalizing the detailing process in AD, formalizing the mappings and incorporating the definition of modularity by Ulrich [13]. In Section 5, we describe experiences from the application of the framework in an applied research project and thus show its utility. We thus bring the industrial and the academic world back together.

2. EXISTING DEFINITIONS OF MODULARITY

Definitions in Academia

The topic of modularity was probably first dealt with by Simon who treated it under the term of near decomposability. "The claim is that the potential for rapid evolution exists in any complex system that consists of a set of stable subsystems, each operating nearly independently of the detailed processes going on within the other subsystems, hence influenced mainly by the net inputs and outputs of the other subsystems" [14]. The focus in Simon's definition is on the minimization of interaction among modules in one domain which he then applied to design, biology and even nation-building.

The definitions that were brought forth in the following [13, 15] were broader and more specific at the same time (Figure 1). They were broader, because it was recognized that modularity cannot be merely considered within one domain, but also consists of a mapping between domains. Ulrich thus views modularity in the context of a mapping from the functional to the physical domain, i.e., (1) "similarity between the physical and functional architecture of the design" and (2) "minimization of incidental interactions between physical components" [13]. They are more specific because they are focused on technical systems.

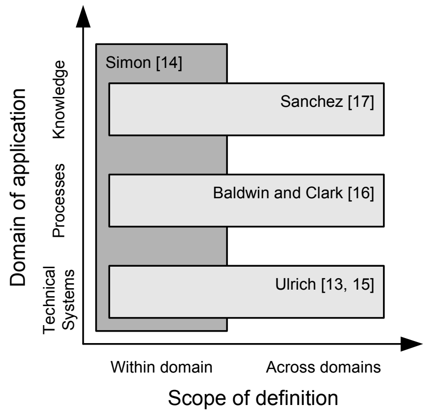

Figure 1. Definitions of modularity in academia.

Modularity was also applied to other fields such as processes [16] and knowledge [17]. The trend has been towards a fragmentation of definitions of modularity in terms of the domain of application. The authors who defined modularity for technical systems generally focused on the functional and physical domains of design and did not consider other domains such as processes or manufacturing. An exception is the work by Miller who applied modularity to Andreasen's theory of domains [18] and thereby extended modularity to the function, organ, and part domains [19].

Definitions in Industry

Ishii and Yang [20] carried out a survey of how modularity is defined in 16 multinational companies. They state that "most descriptions referred to product-oriented practices rather than non-product type practices". The focus in the companies is not so much on a theoretical definition of modularity, but rather on the perceived benefits. Hewlett-Packard uses modularity as a high-level structural approach to determine key components from suppliers. BMW makes use of modularity to rapidly develop components within cost constraints. At Schindler Elevators modularity helps dealing with rapid technological change [21]. At Volkswagen modularity is used to ensure that a complex assembly "can be developed, manufactured and assembled independently" [22].

There is no clear consensus in industry about the benefits of modularity and even less so about a clear definition. Most of the presumed benefits of modularity center on the ideas of better quality, shorter development time, flexibility, and risk management [20]. Interestingly, the perceived pitfalls of modularity are in similar areas, namely lower quality, longer lead times due to module integration issues, lack of flexibility due to rigid structure, and higher risk due to concurrent engineering.

3. AXIOMATIC DESIGN

In this section we describe Axiomatic Design (AD) theory and underline its three principal ambiguities in view of a framework for modular product families. We state these ambiguities in the form of questions, which we will answer through our augmentations in Section 4. The result is the framework for modular product families.

According to Suh "the field of design needs a science base or absolute principles and axioms that can properly guide human endeavor for better creation" [8]. His assumption is that these axioms can be used to determine good design practice. He proposes two axioms, namely the Independence Axiom: Maintain the independence of functional requirements (FRs) and the Information Axiom: Minimize the information content.

These axioms govern the mappings between the different domains of design, i.e., the customer, functional, physical, and process domain. Each of these domains comprises a vector of objects, termed customer attributes {CAs}, functional requirements {FRs}, design parameters {DPs}, and process variables {PVs} respectively. Suh applies the Design Axioms to the mappings from the functional to the physical [8-12] and from the physical to the process domain [8-10] (Figure 2).

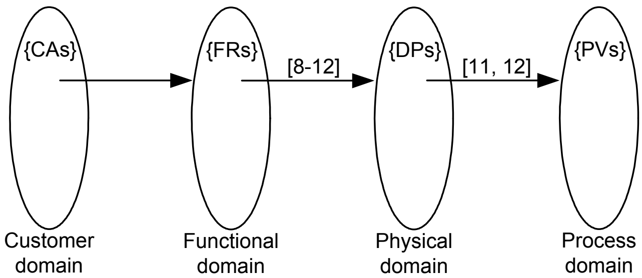

Figure 2. Application of Design Axioms to domains of design.

In [10] Suh maintains that there is hierarchy in the FRs and DPs created through a zigzagging process between the functional and the physical domains. Since the nature of this hierarchy remains unclear, we raise the following questions in view of an augmentation of AD for modular product families.

1. What types of relationships govern the relation between different hierarchical levels in the case of modular product families?

Suh has not explicitly shown in which order a mapping process between the four domains should proceed. This needs to be clarified.

2. How does the mapping process between the four domains look like for modular product families?

Suh points out that "one must zigzag between the domains to be able to decompose the FRs, DPs, and PVs" [11]. Suh thus implicitly states that the customer domain is not part of the zigzagging process.

3. Can the Design Axioms be applied to the customer/functional mapping?

In the following section we will answer these questions by augmenting AD. Simultaneously, we will create the framework for modular product families.

4. FRAMEWORK FOR MODULAR PRODUCT FAMILIES

We now formalize and augment the detailing process within AD, clarify the mapping process between domains, and introduce the concept of modularity. These augmentations pose no restrictions to the validity of the original AD as such. They are just amendments for the purpose of modular product families.

Formalization and Augmentation of Detailing in Axiomatic Design

We formalize and augment the detailing between hierarchies and thereby respond to the first question.

According to Suh "FRs, DPs, and PVs can be decomposed into a hierarchy" [11]. In other words in moving to the next lower hierarchical level the FRs, DPs, and PVs are broken up and part-of relations exist between the two levels. In data modeling this is called a partonomy (Figure 3).

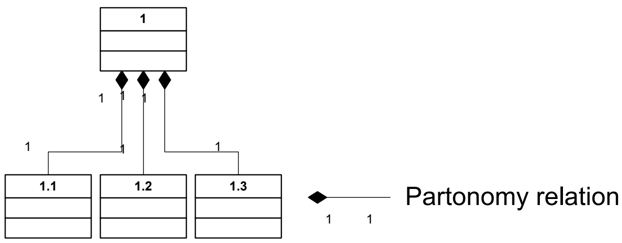

Figure 3. Partonomy.

Yet, the concept of a partonomy is not sufficient if one deals with modular product families. Using a partonomy one can only break up an existing object, but never can one create variation in that object. The concept of variation is however essential to product families. In Product Data Management (PDM) systems this issue is settled by combining partonomy relations with configuration rules. We however suggest augmenting detailing in AD with the kind-of relation, referred to as taxonomy. A taxonomy relation does not alter the system boundaries of an object, but introduces different types of objects within the same boundaries (Figure 4).

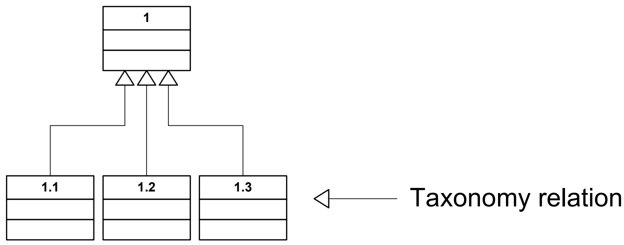

Figure 4. Taxonomy.

Hence, a product family is a range of derivative products that are unified by a common structure comprising partonomy and taxonomy relations where variety is created by the taxonomy relations. This structure can be built up in the functional, physical and process domains. The structure in the functional domain is similar to the function structure used by Pahl and Beitz [23]. The structure in the physical domain is the product structure that is the basis of any PDM system [24]. The relation between the two is generally termed product architecture [6, 21, 25].

Formalization of Mappings in Axiomatic Design

We now address questions two and three by formalizing the mapping process in AD. Suh has made it explicit that FRs, DPs, and PVs are hierarchically structured and that the mapping between these hierarchies is governed by the Design Axioms [11]. He has not made it clear if or how the CAs are structured and how they are mapped to the other three domains.

We are convinced that one should refrain from applying the Design Axioms to the customer/functional mapping as long as two central ambiguities of the customer domain have not been cleared out.

1. *Intracorporate influences*: Suh derives functions exclusively from the customer domain. This assumption is impracticable, because no company can or ever will work this way. In setting up functional requirements one has to account for intra-corporate influences outside the customer domain, such as manufacturing, assembly technology, and logistics or even corporate philosophy.

2. *Boundaries of the customer domain unclear*: In order to apply the Design Axioms one needs to clearly define the boundaries of the customer domain. This has not been done so far. We state that this is extremely difficult, possibly even impossible. A company can capture potential CAs through marketing and its sales force. Yet, this process will always be a partial and approximate one, as customers are only aware of many CAs on a subconscious level. This issue of elicitation is extensively dealt with in [26].

We believe that there needs to be a clear response to the above ambiguities before one can seriously consider expanding the Design Axioms to the customer/functional mapping. Due to its fuzziness the customer domain cannot yet be incorporated into engineering science. The creation of FRs from CAs is an iterative process between the customer and the company that is carried out either through direct interaction with the customer or market surveys. The process can be supported by attention-directing tools such as Quality Function Deployment (QFD) [27] or Design Structure Matrices (DSM) [28]. The mapping from the functional to the physical and process domains can follow the zigzagging process as described by Suh [10] in any desired order. Thus the overall design process consists of an iterative process supported by attention-directing tools in the early definition of FRs from CAs and a zigzagging process governed by the Design Axioms in the latter mapping of FRs to DPs and PVs (Figure 5).

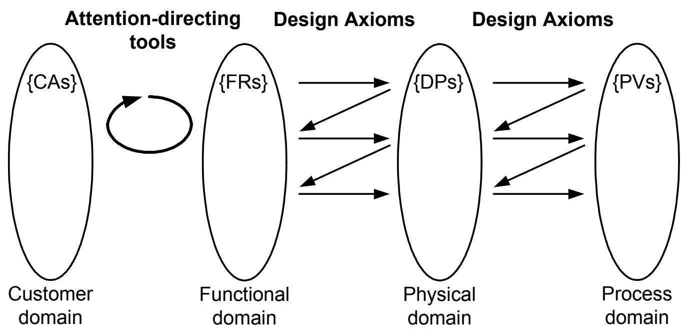

Figure 5: Formalization of mapping process in AD.

Incorporation of Modularity into Axiomatic Design

In Section 2, we stated that Ulrich defines modularity as (1) “similarity between the physical and functional architecture of the design” and (2) “minimization of incidental interactions between physical components” [15]. Chen et al. recognized that Ulrich’s definition of modularity “is rooted in Suh’s Axiomatic Design, particularly the Independence Axiom” [29]. The three degrees of fulfillment of the Independence Axiom can be mapped to Part (1) of Ulrich’s definition of modularity (Table 1).

Independence Axiom in AD	Part (1) of Ulrich’s definition of modularity
Uncoupled	Completely modular
Decoupled	Partly modular
Coupled	Integral

Table 1. Mapping of Independence Axiom to Ulrich’s definition of modularity.

Ulrich's definition of modularity also has a second part to it, namely the "minimization of incidental interactions between physical components" [15]. This cannot be captured in the original AD, because Suh is only concerned with the independence of DPs in contributing to the fulfillment of a particular FR. The interaction among DPs taking place for that purpose is not considered. In other words, Suh focuses on interdomain relations, whereas Part (2) of Ulrich's definition of modularity is a question of intradomain relations.

We resolve this issue by adding interfaces capturing the intended and unintended interactions among modules. Interfaces need to be considered in moving from a higher to a lower hierarchical level, i.e., in the course of detailing. Thus, interfaces need to be defined every time a partonomy relation is introduced (Figure 6). A taxonomy relation on the other hand does not require the definition of interfaces as the module is refined while its boundaries remain unaltered.

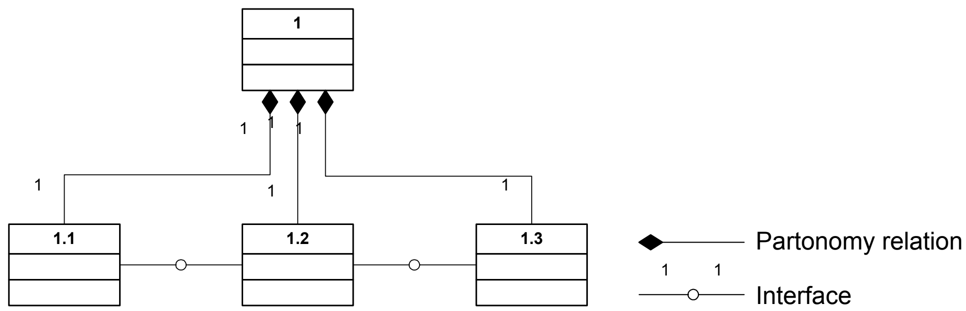

Figure 6. Introduction of interfaces to partonomy relations.

In summary, the framework for modular product families based on Axiomatic Design comprises the following building blocks.

1. *Axiomatic Design* by Suh [8-12]

2. *Taxonomy relations and partonomy relations with interfaces* in the functional, physical, and process domains (Figures 3, 4, and 6)

3. *Mapping of Ulrich's definition of modularity to Independence Axiom and interfaces* (Table 1 and Figure 6)

4. *Formalization of mapping process* (Figure 5)

5. UTILITY OF THE FRAMEWORK FOR MODULAR PRODUCT FAMILIES

In the introduction we outlined that the framework for modular product families should (1) integrate the most widely used academic definition of modularity, (2) be highly structured, and (3) support the development of modular product families. In Section 4 we built up the framework systematically based on AD and mapped Ulrich's definition of modularity to the Independence

Axiom and interfaces. We therefore claim that Requirements (1) and (2) have been fulfilled. The remaining requirement, i.e., the support provided for modular product families in industry is discussed in this section. This is done by describing the experiences from using the framework within an applied research project with three industrial companies.

Using the Framework for Implementing Modular Product Families

Working in highly fragmented markets with lot sizes close or equal to one, our industrial partners decided to embrace to the concept of modular product families. The focus of these families is on the reuse of objects from the physical domain. The framework was applied to the functional and physical domains and offered a guideline in this context (Figure 7).

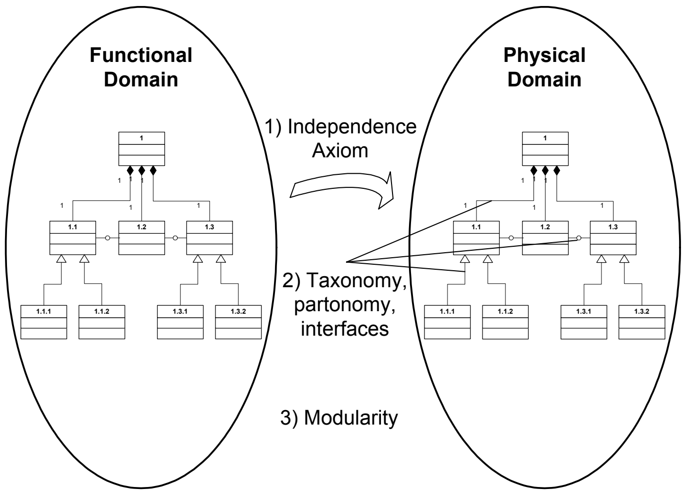

Figure 7. Application of the framework.

The framework supported the product family projects at our industrial partner in three key areas, which we will describe in the following.

Core and Adaptive Modules

We applied the framework to the functional and physical domains respectively. In all cases we observed a structure similar to the one shown in Figure 8.

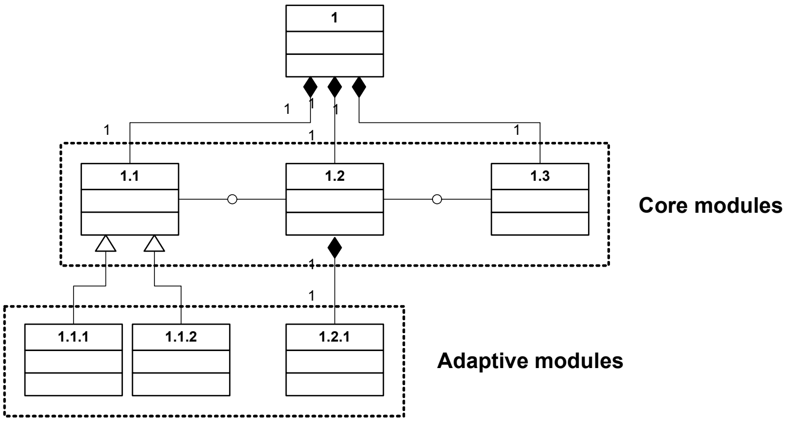

Figure 8. Generic structure observed.

In this generic structure the product family always consists of a set of core modules on the top level (Modules 1.1, 1.2, and 1.3). These modules represent the core functions of the product family. The core modules are generally part of any product delivered by the company and represent the boundaries of what a company is capable and willing to offer to the customer. The core modules are the result of a deliberate market segmentation, targeting, and positioning process and are apparent in the framework.

Below the core modules are adaptive modules that are either particular implementations of the core modules linked by taxonomy relations (Modules 1.1.1 and 1.1.2) or additional, optional modules to a core module (Module 1.2.1).

There are thus two principal types of modules. Core modules, on the one hand, comprise what is constant and strategic within a modular product family, namely the strategic market positioning and the definition of what one is willing and capable of offering to the customer. The adaptive modules, on the other hand, comprise what is variable and are therefore used to provide customization.

Multiple Levels of Modularity

In applying the framework, we observed that the product families are generally modular on the high levels of the hierarchy but integral on the other levels. In other words the high-level components satisfy the Independence Axiom and incidental interactions are minimized. This is not the case for low-level components. There is no clear mapping between domains and the Independence Axiom is therefore not satisfied. Besides, there are multiple interactions. As a result, it is hard to make modifications on this level. The trend at our industrial partners is to expand modularity from the top level to the lower levels by clearly specifying the boundaries of components and their interfaces.

Consideration of Additional Domains

Currently, the focus at our industrial partners is on modularity in the functional and physical domains as it has traditionally been in the literature (Section 2). The objective is however to incorporate the customer and process domains (Figure 9). At one company, the CAs have been structured with respect to the functional domain in order to target particular markets.

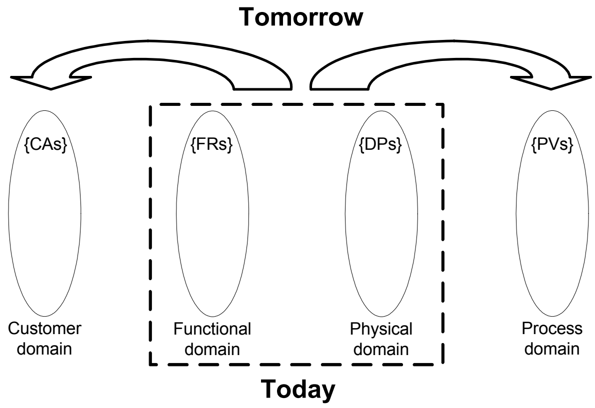

Figure 9. Expanding the scope of modularity.

At the same time manufacturing and logistics are started to be considered in the context of the modular product family. The framework is thus being expanded to the process domain.

6. CONCLUSION

A framework for modular product families has been presented that is based on Axiomatic Design (AD). AD has been augmented with a formalization of the detailing process and its mappings. The Independence Axiom has been mapped to the first part of Ulrich's definition of modularity and the second part of the definition has been incorporated by introducing interfaces. The utility of the framework has been shown in an applied research project.

The primary conclusion we draw is therefore that a rigorous framework for modular product families based on AD is a path that should be followed further. We are currently directing our efforts to applying a greater degree of this framework at our industrial partners. We also conclude that a modular product family needs to incorporate both partonomy and taxonomy relations and not just partonomy relations as in original AD (Section 4). Besides, the customer domain is currently quite ill-defined as its boundaries and detailing are unclear. As a result the Design Axioms can currently not be extended to the customer/functional mapping (Section 4). Modularity may exist on several levels of a product family. Many products are modular on the level of main components, but integral on the level of minor components. The trend is towards expanding modularity to the lower levels as well (Section 5).

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