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THREE PERSPECTIVES ON MODULARITY – A LITERATURE REVIEW OF A PRODUCT CONCEPT FOR ASSEMBLED HARDWARE PRODUCTS

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A Literature Review of a Product Concept for Assembled Hardware Products

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Comments welcome

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Abstract

In recent years, *modularity* as a design strategy has received renewed interest. The term *modularity,* however, is often used to describe phenomena that are similar yet slightly different, for different products, and in different industries and contexts. Therefore, it is unclear whether there is a way to operationalize the concept of modularity across these different uses. This paper reviews the concepts of modularity used in the literature representing different thought worlds (engineering and management) and different occupations (academia and industry).

To find the essentials of modularity I develop an analysis framework consisting of three perspectives. These three perspectives allow to map out and interpret how the different uses of modularity relate to each other. First, the system perspective investigates whether references are concerned with a product's elements (i.e. components/modules), with the relations (i.e. interfaces) between its elements, or with both. Second, the hierarchy perspective illustrates how approaching modularity from either technical details or from a market perspective can result in different interpretations of modularity. Third, the life cycle perspective explains how different goals lead to different, often conflicting, module formations.

The analysis of the modularity concepts from three different perspectives demonstrates that modularity is not one feature but rather a bundle of product characteristics. Which of these characteristics are emphasized and which are understated depends on the different interests constituents express on a product throughout a product's life. Consequently, the term *modularity* alone is of limited use to describe product architectures. One suggested solution is a multi-dimensional product architecture description to help linking individual product characteristics to observable consequences.

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1. INTRODUCTION

Over the last decade, there has been a growing interest in *modularity* – both in academia and industry. Modularity has been described as enabling faster product development (Thomke and Reinertsen 1998) and allowing to produce a large product variety at low cost (O'Grady 1999). Modularity is supposed to provide the customer with almost endless opportunities to customize his product (Pine 1993), and modularity has been identified as harnessing unparalleled innovation rates (Baldwin and Clark 2000).

Beyond the ubiquitous example of the personal computer, recent product examples that claim to be modular, range from small electronic devices to entire subsystems of the automobile. For example, Handspring designed its PDA (personal digital assistant) with a slot to fit in modules that turn the handheld device into an MP3 player, a camera, or a telephone (Biersdorfer 2001). In the automotive industry, cockpits (Anonymous 1999e) or front-ends (Anonymous 2001b) are to be delivered as modules.

But what exactly is *modularity*? Are there different levels of modularity? Can products be more or less modular? Does a product consisting of modules exhibit modularity? And what determines a module? While this paper does not claim to find the final answer to all these questions, it undertakes the task of reviewing the recent streams of literature on the topic of modularity and attempts to relate the various terminologies and interpretations of modularity to each other.[1]

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[1] Sometimes interchangeably used, sometimes understood as a consequence of modularity, but in any case closely related are concepts like *mix-and-match*, *variety*, *(mass) customization*, *product platform*, and *product family*. This paper's goal is not to write a handbook about all possible uses of these terms. It does attempt, however, to put these concepts in perspective to its main focus, i.e. modularity, whenever necessary.

The literature - from engineering background or management fields, published in academic journals or the trade press - offers many different definitions for modularity, often overlapping yet slightly different. For example, some focus on technical function containment as the characteristic module feature, for others the option for the user to be able to re-configure the modules, and thus the product, is the key point for modularity, and yet others emphasize complexity reduction during assembly as representative for modularity.

To extract the essence of modularity, i.e. to find the common elements used across disciplines and to improve the understanding of the remaining differences, I develop a three-perspective framework to analyze the literature along the dimensions *system, hierarchy,* and *life cycle*. The three perspectives help to illustrate that *modularity* really is a bundle of product characteristics, and different views emphasize different pieces of this bundle. As a consequence, it may be advantageous to link the individual product characteristics themselves to the desirable (or undesirable) effects rather than employing an aggregated concept like *modularity*.

Two boundaries define the scope of this paper. The first boundary defines the literature considered. Although it has been found that the concept of modularity (or parts of it) is used in disciplines as diverse as psychology, biology, American studies and mathematics (Schilling 2002 forthcoming), this review is focused on the literature bodies in engineering and management of technology. The stream of literature that applies modularity concepts to organizational designs and institutional structures often exhibits some overlap to product modularity and is considered where appropriate. Furthermore, although the emphasis of this paper is placed on academic literature, some industry definitions of modularity are also included to consider the practitioners' viewpoints. While this review does not claim to be perfectly exhaustive, it analyzes a selection that I feel can be understood as representative for the current state of research on modularity.

The second boundary defines the subject of analysis. This review is concerned with modularity concepts and ideas for industrially manufactured and assembled hardware products. While a number of similarities between hardware and software products exist, some fundamental differences do remain. Therefore, this paper restricts its review to hardware products.

The remainder of this paper is organized as follows. The next section presents the framework and explains its three perspectives. Sections three through five apply the three perspectives *system, hierarchy,* and *life cycle* to the literature body. The systems perspective discusses how differences in importance placed on elements (modules) and/or relations (interfaces) can result in different understandings of modularity. The hierarchy perspective investigates how the understanding of modularity depends on its development path, i.e. whether the modularity definition arose from a focus on the product technology, or whether it was achieved by decomposing a market driven top-down approach. In the fifth section, the life cycle perspective explores how the different loci along the product's life cycle that individual researchers choose can affect the understanding of modularity. Finally, section six summarizes the findings and concludes with a discussion of possible interpretations and future research opportunities.

2. THE FRAMEWORK: THREE PERSPECTIVES ON MODULARITY

This paper analyzes works from different thought worlds and from different occupations. The thought worlds include engineering, management and operations management[2] and the occupations encompass academia and industry. Each of these worlds typically has its own way of looking at problems and definitions, and so they do for *modularity*. Herein lies one of the sources for the confusion that often accompanies the term *modularity.* For example, the more management oriented literature often describes 'modularity' on a relatively abstract level as having standardized and interchangeable components: "modular design [is] a unit or group of standardized elements or parts that may be used within a number of different products" (Galsworth 1994, p.195), or "a modular system is composed of units (or modules) that are designed independently but still function as an integrated whole" (Baldwin and Clark 1997, p.86). In contrast, the literature based in the engineering world mostly focuses on developing designs or design guidelines for specific purposes. As a consequence, the resulting module definitions focus on particular applications, like product functions (Stone et al. 2000a), production requirements (Siddique et al. 1998), or material contents (Newcomb et al. 1998).

While these differences reflect to some extent the origins of the works (engineering works tend to focus on technical details, management articles on market relevant aspects), there are additional differences that can be found across and within these literature bodies. For example, while some sources focus on the subsystems' definition ('customer's choice to mix-and-match

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[2] Of the engineering thought world, the majority of the references are taken from design engineering since *product modularity* is the focus of this paper. The management literature reviewed is centered in the management of technology arena. Finally, I consider a small set of the operations research/operations management literature, which, although small, does cover some important assumptions for the understanding of modularity that are common in this field. The appendix presents all references in two lists: one for engineering literature and one for management literature (including operations management).

components'), other discuss in detail the interfaces ('must allow non-destructive separation'). Again others consider both aspects important ('one-to-one mapping *and* decoupled interfaces').

Finally, more differences across and within the literature bodies are represented by the understanding of modularity with respect to the life cycle phase under consideration. For some, modularity allows the optimal execution of design tasks, for others the efficient organization of production, and for yet others it allows the customer to re-configure her product. Interestingly, these 'modularities' can be very different.

How can all these different viewpoints be reconciled? Is there a way to improve the coherence within and to bridge the gap between the different thought worlds? In other words, can the modularity descriptions from the management literature be operationalized and can the prescriptive models from the engineering literature be generalized?

If definitions and descriptions of modularity are made with various backgrounds and in various contexts, it seems worthwhile to use multiple perspectives to search for common elements and remaining differences. For this reason, a multi-dimensional framework is proposed to distill the common aspects of modularity and to understand when and why additional, perspective-specific aspects occur. Three perspectives represent the lenses through which the often overlapping yet slightly different modularity descriptions can be investigated (Figure 1).

The first perspective views the product like a system. Analogous to a system, a product can be described via its elements and the relations between them. This view helps to clarify some of the underlying features of interchangeability. I call this view the systems perspective. The second perspective views modularity from opposing ends of the product development path. Modules based on functionality from a technical viewpoint can differ considerably from those defined from a market viewpoint. This view is named the hierarchy perspective. The third perspective investigates how the choice of one phase of the product life cycle over another can result in stressing some aspects of modularity while pushing others to the background. This third view is the life cycle perspective.

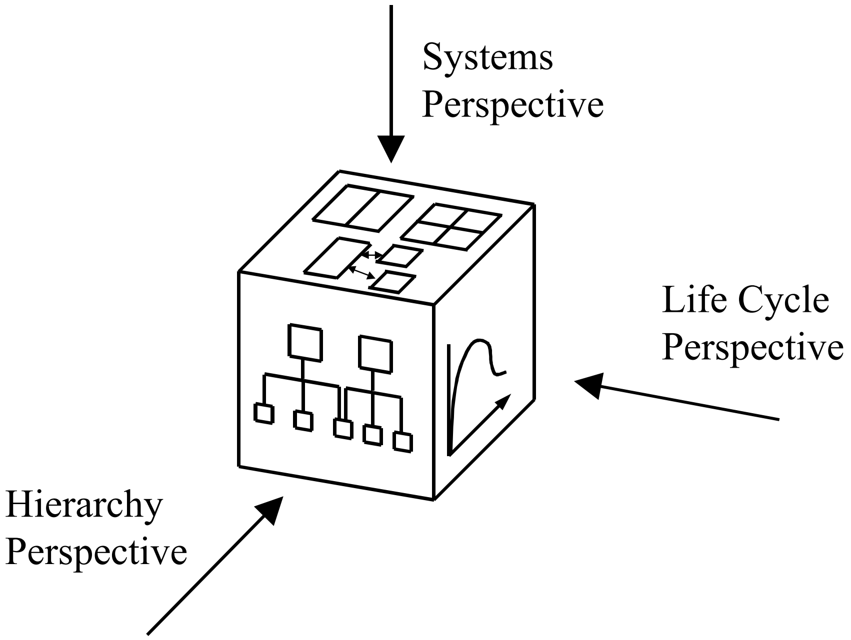

Figure 1: Three perspectives on modularity

In contrast to other literature reviews that cover an extensive field of research (see, for example, Finger and Dixon (1989a, 1989b) for an extensive review of research in mechanical engineering design) the analysis presented here is rather guided by a phenomenon (modularity). Consequently, this framework does not cluster the literature into groups but rather uses the perspectives of the framework as lenses through which it reviews the literature. Because more than one aspect might be considered in a single reference, some sources will be discussed from more than one perspective. The ultimate goal is to grasp the underlying assumptions and elements of product modularity that are used throughout the literature and to develop an understanding of how the different definitions and viewpoints relate to each other.

3. SYSTEMS PERSPECTIVE: DO MODULES DETERMINE MODULARITY?

Trying to capture what *modularity* is, or how the term is used by various scholars and practitioners, leads quickly to the related question of what is a *module.* The lowest common denominator of most descriptions of modules is probably the notion that they exhibit relatively weak interdependencies between them and relatively strong interdependencies within them (e.g. Alexander 1964, Ulrich 1995, Baldwin and Clark 2000, Schilling 2000). The attempt to operationalize this notion, however, leads to a number of additional questions. For example, how are gradations of interdependencies between modules distinguished as representing different levels of modularity? And how are they compared to various levels of dependencies within modules? In addition, if modules are a precondition for modularity, are products with more modules more modular than products with fewer modules? Or, is the level of modularity also affected by the modules' own characteristics (size, function, etc.), and if so, are the averages or the extreme values of the characteristics indicating the whole product's level of modularity?

On a very generic level, there seem to be two fundamental dimensions which many product descriptions and analyses employ: (1) the elements the product consists of and (2) the relations (i.e. interfaces) between these elements. Researchers and practitioners have used and interpreted these dimensions in different ways, emphasizing different aspects. Three sets of this research are discussed below: the works, who focus primarily on the relations a product exhibits between its elements, the works who concentrate on the elements themselves, and those works who combine both dimensions (Figure 2).

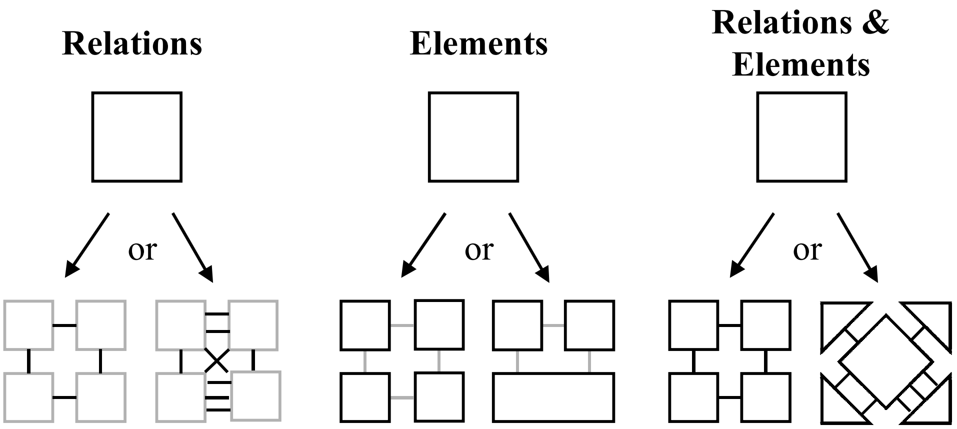

Figure 2: Systems perspectives: three different foci for product decomposition

3.1 Relations only (Interfaces)

In the first group, most researchers focus exclusively on the dimension *relations*, arguing that any determination of the elements (i.e., their content, functionality, size, location, etc.) unnecessarily constraints the analysis. Baldwin and Clark, for example, avoid the dimension *elements* altogether but rather focus on the implications of interface specification for the design process (2000).[3] Often, the dimension *element* is only implicitly addressed while the main focus is on the interface dimension: "Production of components conforming to standard interface specifications also leads to modularity." (Garud and Kumaraswamy 1995, p.94)[4] or "a *modular product architecture* [..] is a special form of product design that uses standardized interfaces

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[3] However, they implicitly introduce an upper bound for a module's complexity: "A complex system can be managed by dividing it up into smaller pieces and looking at each one separately. When the complexity of one of the elements crosses a certain threshold, that complexity can be isolated by defining a separate abstraction that has a simple interface. The abstraction hides the complexity of the element; the interface indicates how the element interacts with the larger system." (Baldwin and Clark 2000, p.64) While 'complexity' can have multiple dimensions, it is conceivable that there is some relation between a module's complexity and other measures for its role within the product, i.e. its size, its functionality, etc.

[4] Garud and Kumaraswamy add that a mix-and-match capability is at the root of their definition: "Modularity allows components to be produced separately and used interchangeably in different configurations without compromising system integrity." (Garud and Kumaraswamy 1995, p.94) While this implies that levels of functionality are somewhat defined for the components, nothing is said about the characteristics of this functionality.

between components to create a *flexible* product architecture (Sanchez and Mahoney 1996, p.66, *italics* theirs). Standardized interfaces (for component exchange) have also been the centerpiece of Starr's concept of modular production: "It is the essence of the modular concept to design, develop, and produce those parts which can be combined in the maximum number of ways" (Starr 1965). This focus on interfaces with respect to modularity is particularly strong in assembly dominated industries. For example, the automotive industry's heavy emphasis on modules' roles in assembly[5] results in a view that almost neglects the elements' (modules) role for the product function: "'Modules' are groups of components arranged in close physical proximity to each other within a vehicle, which are often assembled by the supplier and shipped to the VM [vehicle manufacturer] for installation in a vehicle as a unit. Modular instrument panels, cockpit modules and door modules are examples." (Delphi 1999).[6]

Common element for the set of researchers focusing on the relations between elements (i.e. modules) are the notions of "standardization" and "interchangeable." While technical details still differ along other dimensions (e.g., interface design), these notions imply the existence of a certain number of alternatives for the elements with equal connection points.

3.2 Elements only

Researchers in the second set have placed their emphasis on the dimension *elements.* Often, this emphasis stems from the process of aligning the product's functions and requirements with its physical components (e.g., Erixon et al. 1996). On a conceptual level the idea of product

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[5] Common in the auto industry, is a distinction between modules and systems. The latter focuses on product function, while the former is mostly associated with assembly (Mercer 1995).

[6] This definition is taken from Delphi's 1999 10k-report. Other automotive suppliers and OEMs use similar definitions.

decomposition seems straightforward, as Alexander quotes Plato: " … the separation of the Idea into parts, by dividing it at the joints, as nature directs, not breaking any limb in half as a bad carver might." (in Alexander 1964, preface). To operationalize this concept, however, is much more difficult and researchers have chosen various approaches which can be clustered into three sub-groups. These sub-groups can be distinguished by the extent to which they consider architectural changes in the way functions are allocated to the product's elements (Figure 3). In the simple case, the elements' functional boundaries are fixed and only predetermined sub-units can be exchanged. The medium case allows to 'collect' smaller elements into larger ones to 'form' modules. Finally, the fundamental case permits a complete re-allocation of functions to the elements. Each of these cases is discussed in turn.

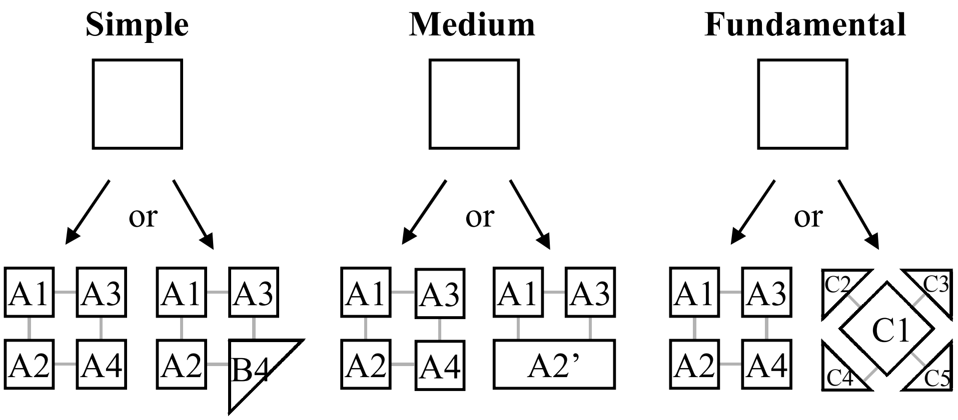

Figure 3: Elements can vary in multiple ways[7]

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[7] As an abstraction, assume that the area of the larger squares symbolizes product functionality, i.e. all three cases represent identical levels of functionality. Then the different ways of decomposition illustrate variations in the way the functionality is allocated to the product's elements (sub-units, components, chunks, modules, etc.).

3.2.1 'Simple' (Element replacement)

First, in its most simple case, the architecture is predetermined and only elements that contain a certain function or feature can be varied (A4 or B4, simple case in Figure 3). Examples are color changes of face-plates (e.g. at cell phones) or the use of different power sources in otherwise identical products (e.g., power tools). Coulter et al. also follow this idea to determine the optimal material choice for each component to achieve best recyclability of an automotive center console (Coulter et al. 1998). They apply an optimization approach that alters the materials for each component to minimize the number of different materials per pre-selected module (component group). Characteristic for these 'element replacements' is that they cannot differ to an extent that the product functionality is endangered, i.e. they must contain the function or feature that is to be changed (or varied).

This approach can also often be found in the operations research world. For instance, models developed to identify potential gains from parts commonality implicitly assume interfaces that guarantee total interchangeability of components or modules. Using this simplification, some models investigate the effect of parts commonality on safety stock levels (Collier 1982, Baker et al. 1986), or how parts commonality affects supply chain costs (Ernst and Kamrad 2000). Other works assume components as interchangeable but allow them to differ along a performance dimension or quality to allow for creating product variety. For components that impact the product quality only weakly or indirectly[8], the analyses focus on balancing cost penalties from overdesign with cost savings from commonality. For example, Fisher et al. investigate the factors that determine the number of different brakes across a car family (Fisher

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[8] A component's quality affects the product quality only indirectly if a the component quality level (above a certain threshold) does not differentiate the product from the customer's perspective.

et al. 1999), or Thonemann and Brandeau develop algorithms to find the optimal level of commonality for automotive wiring harnesses (Thonemann and Brandeau 2000). For components whose quality level does impact product quality, Desai et al. model how to balance the revenue and cost effects of commonality for the different quality levels of the components (Desai et al. 2001).[9]

Another research approach that fits into this subset of approaches is 'group technology.' It advocates "to exploit similarities and achieve efficiencies by grouping like problems (Hyer and Wemmerlov 1984, p.4). Primarily focused on forming part families, this grouping is suggested along multiple dimensions such as design, material, manufacturing process planning & cell design, or purchasing criteria (Suresh and Kay 1998). From a product perspective, this argues also for interchangeable components.

With respect to modularity, the 'simple' case of element exchange mirrors what has been termed parametric design, i.e. the product architecture is fixed and characteristics are varied only within the boundaries of the elements (e.g., material, quality, color, etc.). This approach includes almost always two assumptions: the exchanged elements provide identical interfaces and the replacement must not compromise system function.

3.2.2 'Medium' (Packaging problem)

The second sub-group of decomposition approaches assumes the smallest building block of the architecture, the basic elements, as fixed, and produces the product architecture by arranging

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[9] Fisher et al. (1999) categorize a product's components into two groups. One encompasses all components with a strong influence on product quality and the other includes all components with a weak influence on product quality. In their analysis Fisher et al. focus on the latter category to model cost trade-offs. Thonemann and Brandeau 2000 follow the same idea. In contrast, Desai et al. (2001) model explicitly the impact of quality differences on both cost and revenues. Even so, they also model the quality difference as confined to the element (component) itself, and assume perfect component interchangeability.

(and re-arranging) these components into (larger) modules (A2+A4 or A2', medium case in Figure 3). For instance, for a vacuum cleaner, should the motor and the fan jointly form one module or two separate ones? In essence, this approach presupposes existing, basic elements, and the architecture definition is reduced to the determination of how these elementary elements are grouped into larger ones (i.e. the modules).

The criteria used to group the elements into modules vary across research fields and along the product's life. For instance, for products where the expected innovation rates of the underlying technology differ across components, it has been suggested to group components with similar innovation rates into modules (Langlois and Robertson 1992, Martin and Ishii 2000). Others have focused on reducing development time or expenses (Roemer et al. 2000) or improving the product's end-of-life environmental performance (Newcomb et al. 1998) as criteria driving the module formation process. One major tool developed to help in this module formation process are interaction matrices.[10] Some matrices document types and importance of interactions (Pimmler and Eppinger 1994), others indicate the components' levels of suitability to belong to the same module along multiple criteria (Huang and Kusiak 1998, Kusiak 1999). In most cases, columns and rows are re-arranged to minimize the unwanted interaction or to increase the desired 'similarity.' Genetic algorithms have also been suggested for this clustering process (Gu et al. 1997).

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[10] Many variations of matrices most current day authors use to determine how to form modules go back at least to some extent to the work of Steward (1981). His design structure matrix (DSM) is the basis for many derivatives. Browning categorizes the many different types of what he calls Dependency Structure Matrices into four groups: (1) Component based or Architecture DSM, (2) Team-based or Organization DSM, (3) Activity-based or Schedule DSM, and (4) Parameter-based or (lowlevel) Schedule DSM (Browning 1998). The first deals with functional interactions while the product is in use, the second with development team interactions. Both cases have no time component and most optimization algorithms applied to these problems attempt to distribute the product's complexity to some extent evenly (1), or try to align functional product interaction with development personnel interaction (2). Cases 3 and 4 include an order or sequence of information, and optimization algorithms used for this type of DSM strive to reduce the amount of iterations during the development.

The ‘medium’ approach is also used in works that measure the impact of shifting the point of module formation in the production process on production costs (Ishii et al. 1995) or in the investigation of the differences in service costs for multiple configurations of a document handling system of a copy machine (Dahmus and Otto 2001).

This approach’s underlying assumption is that functions are clearly defined on the level of the lowest, basic elements. Returning to the vacuum cleaner example, this means that the motor and the fan have distinctly separate functions. They can be combined, but they are not divisible. The possibility that some fraction of one element’s function, say the motor, is delivered by another component, does not exist. In other words, building a matrix and filling it with the product’s basic elements, establishes already the first layer of product architecture.

Common for these ‘configuration’ processes is that modularity is defined in approaching an optimum that combines elements into modules according pre-set criteria. Although module boundaries vary according to the different criteria, in general, the goal is (a) to group ‘similar’ elements and (b) to transform interactions between modules into interaction within modules.

3.2.3 ‘Fundamental’ (Re-arranging of function to components)

While the second subset was constrained by the pre-definition of sub-module level components, the third subset relaxes this constraint. This approach attempts to capture truly distinct product structures – designs that differ fundamentally in the way functionality is allocated to the elements (see fundamental case in Figure 3). As an illustration, consider the example of a computer. The medium approach would take basic elements and group them into modules like display, CPU, hard drive, energy unit, keyboard and mouse. In contrast, the fundamental approach allows to describe the architectural difference if, for example, the data input function (typing) is re-allocated from the keyboard to, say, the display (‘touch screen’).

One way to find new function-component allocations is to map the functions on *potential* modules and then assess the viability of these potential modules along various criteria (O'Grady 1999). While this approach might create a new allocation scheme, it does so within the constraints of existing components. To overcome this problem requires a higher level of abstraction. Using customer needs and fundamental, basic functions McAdams et al. compare different products to identify possible common modules (McAdams et al. 1998). They abstract the product functions required by customers into fundamental functions (e.g. convert electricity to rotation, import human hand and import human force, etc.) and analyze similarities between small household appliances like icetea-makers, coffee-makers, and palm grip sanders. Following a similar idea, Dahmus et al. compare function structures for common and unique functions across a product family to define possible product architectures (Dahmus et al. 2001). Obviously, these approaches offer some unique challenges. For example, how are functions compared and weighted with each other? Currently, most researchers use some sort of weighting scheme – either implicit or explicit. Research work that proposes optimization procedures (or design guidelines) often recommends interdepartmental negotiations to agree on these weights.

Compared to the previous ‘medium’ sub-group, this ‘fundamental’ sub-group uses a higher level of abstraction (physical function instead of basic components) to create the product architecture. To some extent, this abstraction also carries implicitly conditions for the module formation and interface definition (for example, ‘convert electricity’ requires certain materials and excludes others). It does so, however, on the least specific level of the three sub-sets.

3.3 Relations and elements

The third research set of the systems view combines the ideas of the two dimensions *elements* and *relations*. Its proponents argue that both dimensions are required for a complete description of modularity. One research approach using such a composite definition suggests the product architectures as a means to describe and determine levels of modularity. In his influential 1995 article, Ulrich defines the product architecture as "the scheme by which the function of a product is allocated to its physical components." He distinguishes two archetypes of product architectures: "A modular architecture includes a one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components. An integral architecture includes a complex (non one-to-one) mapping from functional elements to physical components and/or coupled interfaces between components." (Ulrich 1995, p.422) This model of a modular-integral dichotomy has been employed in a broad range of fields, ranging from engineering (Allen and Carlson-Skalak 1998), to strategy (Chesbrough and Kusunoki 1999), to theory building (Schilling 2000).

Another method that also considers the arrangement of functional elements, the function structure mapping and the interface specifications, i.e. both elements and relations, has been proposed by Martin and Ishii. To support product family development, they suggest to measure (a) the innovation rates of components and thus their likelihood to change, and (b) the extent to which changes in one component trickle through the rest of the product and propose to make qualitative assessments of both (Martin and Ishii 1996, Martin and Ishii 2000).

Some practitioners also use module definitions that include both dimensions, i.e. elements and relations: A module is a "complex assembly forming a closed function unit which permits specific differentiation and which, as a consequence of defined interfaces (function, geometry), can be developed, manufactured and assembled independently" (Wilhelm 1997).

This third set of research can be considered as a more complete product architecture description compared to the previous two by combining both dimensions. However, it still is difficult to operationalize because it remains unclear how different feature combinations along the two dimensions result in different levels of modularity. Section 6 will return to this question.

4. HIERARCHY PERSPECTIVE: BOTTOM-UP OR TOP-DOWN MODULARITY?

Almost four decades ago, Herbert Simon noted that complex systems tend to organize themselves in hierarchies (Simon 1962).[11] Others have found that almost all products are themselves part of 'nested hierarchies,' i.e. while exhibiting an internal hierarchy they are simultaneously part of an upper-level hierarchy (Christensen 1992a, Gulati and Eppinger 1996, Baldwin and Clark 2000, Schilling 2000).

This section examines the literature with respect to the direction of its approaches. It is not so much the level of analysis that differs between the searches for definitions and descriptions of modularity, but rather the viewpoints from which researchers begin their analyses and descriptions. Clark has pointed out the existence of multiple hierarchies. He makes a "distinction between hierarchies and associated resources linked to product and process technology, and those linked to customers and markets." (Clark 1985, p.249) In analogy to this distinction I will present two vantage points from which the modularity issue has been pursued.

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[11] Simon defines a complex system as "one made up of a large number of parts that interact in a nonsimple way." (Simon 1962, p.468)

The first one is a bottom-up approach grounded more in the engineering world, and the second represents a top-down approach based in the market world.[12]

4.1 Bottom-up: How to build a product

The mental framework of the bottom-up approach is rooted in the engineering world. Engineers all over the world are trained and educated to break up problems that are too complex into smaller ones that can be solved. Engineers want to create products 'that work.' This implies that there is something that products 'do' and this 'doing' is nothing else than the function of the product in technical terms. Solving problems in the engineering world is finding ways to create mechanisms that function as desired. Pahl and Beitz, for example, recommend the following four steps for conceptual design: (1) abstract to identify the problem, (2) establish function structure, (3) develop a working structure,[13] (4) evaluate and select best combinations. In subsequent design stages, i.e. embodiment design, the design is completed (Pahl and Beitz 1996). Function structures, the part of interest here, refer to the 'flow' of energy, materials, and signals that 'travel' through the system. They are themselves hierarchically structured (Figure 4).

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[12] There is some overlap with the possible clustering along a unit-of-analysis distinction, like product level vs. product-family level. To cluster the literature along distinction, however, is often difficult, especially when authors later extend their work to include additional level of analysis. In contrast, the original approach is almost always different (Nevertheless, the tables in the Appendix lists in the 'hierarchy' section the unit-of-analysis for each reference in addition to the top-down/bottom-up assessment.)

[13] Working structures describe working principles together with geometric information, such as location and direction. Working principles are physical effects, such as gravity, friction, etc. (see Pahl and Beitz 1996).

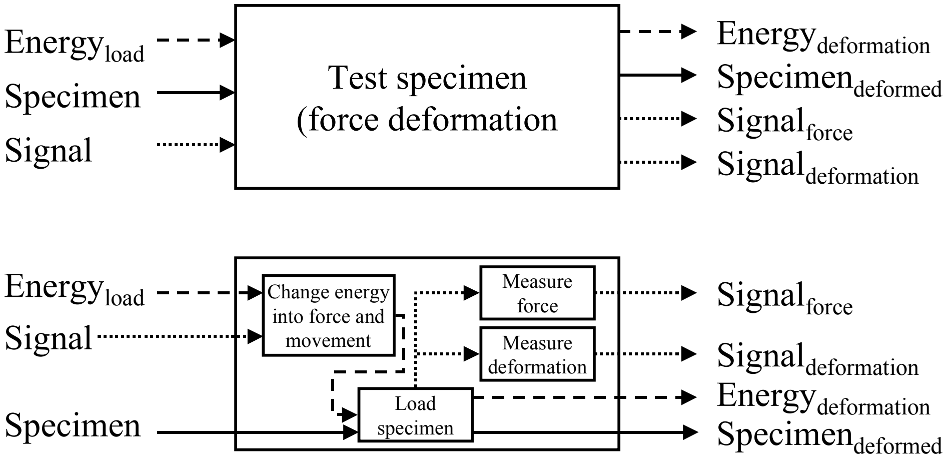

Figure 4: Overall function (top) and sub-functions (bottom) of a testing machine[14]

Having defined functions on these fundamental levels, engineers 'assemble' the products in their mind. That is, functions that are similar, or use the same working principles, can be combined. Precisely this approach has been used to support developing modular products. Stone et al., for example, develop three heuristics to identify possible modules (Stone et al. 1998). The three heuristics they suggest take on the engineers' perspective on functionality: dominant flow, branching flow, and conversion-transmission are all technical views of what the product does.[15] Building on this idea, Stone and other researchers have extended it to increase its applicability to other products (Stone and Wood 2000, Stone et al. 2000a), to include product family considerations (Stone et al. 2000b, Dahmus et al. 2001), or brand considerations (Sudjianto and Otto 2001). Function based module definitions have also been explored to accommodate recycling goals (Allen and Carlson-Skalak 1998).

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[14] Pahl and Beitz 1996, p.152

[15] Dominant flow refers to the highest ranking (from customer needs) non-branching flow (e.g. the specimen in Figure 4), branching flow refers to modules defined by branching function chains, and conversion-transmission refer to conversions of energy or material of one form into another form of energy or material. Note that Stone et al.'s approach also introduces customer needs to evaluate the modules. Basic starting point, however, are the functions in engineering terms.

The characteristic common to all bottom-up approaches is a detailed study of the product's technical functionality, followed by assigning functions or set of functions to elements. Finally, elements a (re-)combined into complete products or product families.

4.2 Top-down: How to serve markets

While engineers view a product as "a complex assembly of interacting components," the marketing perspective sees a product as "a bundle of attributes" (Krishnan and Ulrich 2001, p.3). We will call the approach that begins with the market view on products 'top-down.' Most often, researchers choosing a top-down approach, start with the product's potential or existing market(s), divide the market(s) into categories or segments, and propose architecture(s) to simultaneously serve these market segments. Two conflicting objectives drive this process: (a) the need to offer the customer as much variety as she wants and (b) the need to reduce the variety for cost reason, i.e. to strive for commonality. The fundamental question is how to translate different customer needs and expectations into product (family) architectures.

The way the variation of customer needs is treated is key for this mapping from customer needs to product architectures. Some approaches focus entirely on the extent to which commonality is achieved, others consider different types of customer need variations, and yet others model the tradeoff between commonality and distinctiveness.

In pursuit of commonality, the use of identical parts has received different labels, depending on the level within the product hierarchy and the location in the value chain. For instance, an approach that seeks to reduce variety on the component level, primarily on the shop floor, has been termed group technology (e.g. Hyer and Wemmerlov 1984). Others have focused on the extent to which an existing product family accomplishes the use of common parts and components. Kota and Sethuraman, for example, develop a product line commonality index that measures how far a given product family is away from the (manufacturing) ideal to have identical components (Kota and Sethuraman 1998, Kota et al. 2000). Similarly, MacDuffie et al. have developed composite variables that reflect, among other things, levels of parts commonality for statistical analyses (MacDuffie et al. 1996). On higher levels of the product hierarchy, i.e. if a larger fraction of a product is 're-used' in other products of the product family, the term *product platform* has received considerable attention. A product platform is described as "a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced." (Meyer and Lehnerd 1997, p.39) Some understand the platform as offering a configuration space within which a customer variety can be produced. For example, Siddique et al. develop a product family reasoning system that identifies candidate sets of platforms out of a set of existing products, condition to constraints imposed by other products or assembly facilities (Siddique et al. 1998, Siddique and Rosen 2000).

For a more detailed consideration of customer need variations Yu et al. suggest a customer need analysis that represents customer need target values as probability distributions across market segments and over time (Yu et al. 1999). They also introduce three categories of what they call portfolio architecture: fixed, adjustable, and platform. They find that if the customer need distribution is stable over time and narrow in its distribution a single, fixed architecture is sufficient. If a need distribution exhibits ergodicity, i.e. the need distribution across the population at a single point in time is equal to the distribution of every customer over time, they recommend an adjustable architecture. The requirement for leg room in a car is an example of such a customer need. It is served with a single but adjustable architecture. If the target values of customer needs are not stable over time or across segments, they suggest to isolate the corresponding feature in a module and to use a platform architecture for the rest of the product. As an example they use the cover of a toaster to indicate a need that changes with trends. As another way to offer the customer variety, it has been suggested to create ‘optimal’ building blocks and let customers ‘customize’ their product themselves (Tseng and Jiao 1996, Tseng and Du 1998). To design the building blocks clustering of design parameters is suggested. This approach seems to work well for products where the differentiation is one of scale, i.e. the same component with a different performance level (e.g. power supply switches).

Finally, others model the opposing forces for variety and commonality as a trade-off. For example, Robertson and Ulrich propose a method to balance distinctiveness with commonality. They propose to define the number of chunks (physical pieces) of a product as roughly equal to the number of differentiating attributes (Robertson and Ulrich 1998). Acknowledging that the importance of various factors going into this tradeoff might differ, they suggest an iterative approach as a correction mechanism. The difficulty to handle this multi-factor trade-off is also recognized in other research. For the case of a spacecraft family based on a common design, a negotiation process is suggested to agree on common parameters across all missions (Gonzalez-Zugasti et al. 2000).

In sum, the top-down approaches begin with the understanding of a need for product variety and suggest methods to identify commonality on various levels of the product family and, subsequently, of the product. Common for most of them is the implicit assumption that product variety via a platform approach requires (a) function or feature containment in the module designed to be replaced to create the variety, and (b) interface designs that allow this ‘replacement,’ for the designer, the manufacturer, or the user.

5. LIFE CYCLE PERSPECTIVE: MODULARITY FOR WHOM?

The third perspective discussed in this paper takes on various positions over a product's life time. Every product runs through different phases in its life. Each life phase sets different performance goals for the product. For this reason, a product that is optimized for one phase, is not necessarily optimal for others. Since this is a general design phenomenon, it is not different for developing optimal 'modularity.' Just as numerous approaches have been developed to optimize products for various purposes (e.g. see the DFX literature), a number of methods has been proposed to develop modular products. Depending on the field of application, these techniques arrive at different definitions of what a 'module' represents.[16]

5.1 Design and development

Researchers working on design and development processes are typically concerned with the question of how to reduce the resource consumption (cost & time) for D&D, condition to a certain level of product functionality and quality.[17] Since today's complex products are already beyond what a single human mind can work on, the development of these products is split into work packages which are assigned to various people and teams in the organization. Organizational structures tend to mirror the structure of the products the organization makes (Henderson and Clark 1990).[18] Organizational structures also create a need for communication

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[16] Some have suggested to define 'modularities' for different phases: Modularity-in-Design (MID), Modularity-in-Production (MIP), and Modularity-in-Use (MIU) (Baldwin and Clark 2000, Sako and Murray 1999). As this section will show, this distinction still appears too coarse to make *modularity* operationalizable.

[17] Another concern could be to create product architectures whose development processes allow to design *better* products.

[18] For complex multi-technology products it has been argued that companies need to maintain a broader technology base than what they actually produce (Brusoni and Prencipe 1999).

and efficient communication maximizes the resource productivity. Thus, the question is: what are the architectural characteristics of a product that minimize the resources required to develop it?[19] What are the modules that facilitate the development?

Consequently, researchers have proposed methods that 'modularize'[20] the product, and in turn the design process, such that the communication effort is minimized. The most fundamental account is, that a task that exhibits a low level of interdependence with other tasks, has a higher probability to be successfully solved than a task that has a high degree of interdependence with other tasks (von Hippel 1990). Based on the design structure matrix (Steward 1981) researchers have developed several modeling techniques to predict the impact of product architecture choices via organizational structure on development time and cost (Eppinger et al. 1994, Baldwin and Clark 2000, Ahmadi et al. 2001). On a very generic level, module definitions in these works aim at minimizing the communication effort and at reducing the risk level within larger development efforts.

5.2 Production

If one understands component interchangeability as modularity, then the idea of a simplifying concept in the world of production is already a century old. What Henry Ford accomplished for components *within* a product (line), was proposed by an automotive engineer in 1914 *across* products and for larger components: standardized wheel sizes, hubs, bearings,

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[19] There actually is a two-way relationship between product architecture and organizational design (Gulati and Eppinger 1996). Nevertheless, for the purpose of this paper, I focus on the effect product architecture/modules have on the organizational performance. In addition to the product architecture, organizational decisions alone, , like sequential iteration or overlapping, also influence the efficiency of development processes (e.g. Smith and Eppinger 1997b, Krishnan et al. 1997).

[20] The literature often prefers terms like 'partitioning' and 'task blocks' rather than 'modularization' and 'modules.'

axles and fuel feeding mechanisms (Swan 1914). Half a century later, in 1965, Starr proposed modular production as a new concept to provide product variety. His emphasis on "maximizing the combinatorial variety of assemblies from a given number of parts" (Starr 1965, p.138) implicitly requires function containment within the interchangeable components in order to not compromise the product function as a whole. 30 years later, Pine suggests a similar approach for mass customization (Pine 1993). Although he argues that mass customization targets individual customers while producing variety alone does not necessarily do so, the tools behind it are very similar. Building on Ulrich and Tung's work (1991), he proposes six categories of modularity: component-swapping, component-sharing, cut-to-fit, bus, sectional and mix modularity. Again, these definitions carry implicitly some features for the modules: function containment (otherwise some functionality of the product would be lost), a limited number of different interfaces, and some notion of the ease with which interfaces can be physically connected and disconnected.

In production, 'modules' are predominantly understood as assembly modules. Typical characteristics are the collection of components in/on them and the 'ease' with which the connection can be made. For products that differ only along a few performance dimensions, combinatorial design has demonstrated its advantages (Whitney 1993). Similar views are often found in the automotive industry (Wilhelm 1997, Delphi 1999).

In sum, most module definitions concerned with the product's production phase aim at lowering production costs. Major ideas behind this are economies of scale for modules that can be used across product families, complexity reduction throughout manufacturing and assembly, and inventory reduction through risk pooling and postponement.

5.3 Use

Two aspects fall under the use phase category. First, many module definitions use implicitly the use phase, because they build on the product functionality, i.e. the function the product will perform while it is in use or operation. Most 'module' definitions that originate in the engineering world follow this idea (see discussion in section 3.2 and Appendix). Consequently, function containment is of major importance, albeit sometimes only implicitly.

Second, and even more than for assembly, the 'module' idea during the use phase is focused on a single interface characteristic: the effort it takes to separate it. This is a result of the idea that modularity-in-use allows product re-configuration on an effort level lower than the original production, often enabling the *user* herself to customize or re-configure the product. Similarly, up-grades or maintenance require (a) interfaces that are easy to separate and (b) functionality containment in order to have the desired results. For instance, for service purposes components with equal lifetime or similar failing frequency should be located in one module (Newcomb et al. 1998). In general, due to the similarity to the assembly portion of the production phase, very similar concepts are underlying modularity-in-use.

5.4 Retirement

The final phase of a product's life is its retirement. Two major ways exist for the product, depending on the post life intent. First, it could be refurbished as a whole or its components could serve as spare parts, and second it could be transformed into other use. For assembled products, the former always include a disassembly process, the latter only if either material value makes it economically viable or legislation requires the separation of hazardous materials.

The post-life-intent, for example, can be expressed as material recycling, which makes modules desirable that contain as few different materials as possible (Allen and Carlson-Skalak 1998, Newcomb et al. 1998). To improve existing design's environmental performance, a procedure has been suggested that identifies the constraints, that – if changed – would offer the greatest improvement towards a more environmental friendly design (Coulter et al. 1998). In their example, an automotive center console, the authors change materials, but not the modules' boundaries.

To summarize, the requirements of a post-use phase are often entirely different from those in design, production or use. As a result, module definitions vary again.

6. DISCUSSION AND CONCLUSION

The foregoing discussion analyzed product modularity concepts from three different perspectives. This section recaptures the findings and interprets their meanings with respect to a general concept on product modularity.

The first perspective, systems, has indicated that a product description focusing only on elements or only on relations limits itself unnecessarily. While this may be appropriate for some applications, in search of a more comprehensive understanding of product modularity, the research approach that includes both dimensions appears to be advantageous. Despite being conceptually powerful, however, this approach in its current form is also difficult to operationalize for two reasons. First, while the simultaneous description of elements and relations presents two layers of information, the level of dependency between the two is unclear: Do they change always simultaneously? In other words, can an architecture without a one-to-one mapping from functional elements to physical components have de-coupled interfaces? Or can one with a one-to-one mapping exhibit coupled interfaces? Consider the example of attaching the MP3 module from the PDA example with adhesive bonding instead of a plug. The one-to-one mapping would still exist, but the interface characteristic was changed. It seems that some interface characteristics can change (or be changed) without simultaneously changing the function-component mapping, and vice versa.

Second, and this is somewhat related to the first argument, both dimensions are themselves multi-faceted. The function-component allocation can have different results at different places throughout a product (e.g. one-to-one mapping on one end of product, a non one-to-one mapping at another). How does this affect the modularity assessment of the product architecture? Likewise, interfaces can differ in multiple dimensions. Does 'coupling' mean the interface's role for the product function? For its design? For its manufacturing? Or for its disassembly?

The second perspective juxtaposed two approaches that can be understood as working through a product hierarchy from two different ends. The bottom-up approach 'builds' a product by finding solutions for elementary problems, and then combines these into chunks, modules and ultimately into products, i.e. it 'builds' modules by a combination and aggregation process.[21] In contrast, the top-down approach, often driven by a marketing standpoint, divides markets into segments and identifies product features that need to be separate and others that can be common. The modules, or the product's modularity, are developed from there.

What the review of the literature from this perspective demonstrates, is that whatever is seen as modularity, it is as a result somewhat path-dependent. Only at a single point where the two

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[21] While there are tools to translate market research into technical specifications (e.g. House of Quality, etc.), they typically do so by creating specs along engineering performance dimension.

paths meet, the views are perfectly congruent. Since the paths to this point differ, if any (or both) of the views is not at this common point, the resulting modularity specifications will differ. Up to this point, the bottom-up view uses modularity to describe the artifact, the top-down view uses modularity to describe the features.[22]

Finally, the third perspective viewed modularity for different life cycle phases. All design techniques guiding module creation for a particular phase necessarily prioritize design goals, either implicit or explicit, just as any other optimization approach. While this is a legitimate goal for a particular design task, it makes the term ‘module’ alone less useful to distinguish various types and levels of modularity.

In sum, the literature review offers three major insights. First, product modularity appears to be a bundle of product characteristics rather than a single condition. Function-component allocation schemes and several interface characteristics are both required for a complete description. Second, while function containment is, explicitly or implicitly, part of most modularity descriptions, what is understood as a function, however, can vary with the viewpoint taken. Therefore, a modularity description should identify its own viewpoint. Third, module and interface characteristics are interpreted differently, depending on the life cycle phase. For example, designers emphasize low functional interaction, producers easy installation, and users easy disconnection.

Apparently, there is not a single definition for *modularity* that holds under all circumstances, and is simultaneously operationalizable. Acknowledging the multi-faceted character of module definitions along a product’s life and across various participants’ viewpoints, multi-perspective

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[22] Some recent research focuses on the process of how this gap narrows. The emergence and stabilization of product market categories has been described as social construction processes through ongoing interactions between

approaches might offer more comprehensive understanding of the phenomena. One possibility are simultaneous assessments of different perspectives (Tseng and Jiao 1998, Jiao and Tseng 1999), of different phases (e.g. product, production and sales in Du et al. 2000) or weighting procedures to accommodate the to some extent conflicting objectives (Gu et al. 1997).

A second approach is to un-bundle the product characteristics normally subsumed under *modularity* and to tie them individually to viewpoints and life cycle phases. This approach promises to contribute to a clearer understanding of causes and effects around the phenomenon *modularity*. An ongoing research project develops a taxonomy that permits comparative multi-dimensional product architecture descriptions. This descriptive approach then allows to link the architectural features individually to effects and consequences (e.g. costs, time, etc.) in different life cycle phases.

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producers and consumers (Rosa et al. 1999). Perhaps, the understanding of what constitutes product families, and thus, products and ultimately modules, undergoes a similar stabilization process.

7. APPENDIX

The two tables below list the articles reviewed for this paper. Every article is assessed from the three perspectives *systems, hierarchy,* and *life cycle.* The legend on page 38 explains the meaning of the symbols used in the table. The entire list of articles is split into two groups: one more engineering related, the other more management related.

Table 1: Modularity in the literature - engineering section

Reference	**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Description/ Variations of Elements	Description/ Variations of Relations	Bottom -Up	Top-Down	C	M	P	F	Des.	Prod.	Use	Retir.	
Allen and Carlson-Skalak 1998	1-2	(X)	X			X	X				X	X	Video cassette
Coulter et al. 1998	1	(X)		X	X		X					X	Automotive center console
Dahmus and Otto 2001	2		X		X		X				X		Document handling system of a copy machine
Dahmus et al. 2001	2-3		X		X		X	X			X		Family of electric cordless drills
Du et al. 2000	1-2		X		X		X			X	X		Office chair
Erixon et al. 1996	2-3	(X)		X		X	X			X	X	X	*Concept only*

Reference	**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Description/ Variations of Elements	Description/ Variations of Relations	Bottom -Up	Top-Down	C	M	P	F	Des.	Prod.	Use	Retir.	
Gonzalez-Zugasti et al. 2000	2			X	X		X	X			X		Space craft
Gu et al. 1997	2	X	X		X		X				X	X	Vacuum cleaner
Huang and Kusiak 1998	2-3	X	X		X		X			X			Desk lamp & Electric motor
Ishii et al. 1995	2	(X)		X		X	X	X		X			Refrigerator door
Jiao and Tseng 1999	2	(X)		X		X	X	X			X		Power supply units
Kota and Sethuraman 1998	2			X					(X)	X			Walkman
Kota et al. 2000	2			X					(X)	X			Walkman
Martin and Ishii 1996	2	(X)		X		X	X	X		X			Refrigerator door
Martin and Ishii 2000	2	X		X		X	X	X			X		Ink jet printer; thermoelectric water cooler

Reference	**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Description/ Variations of Elements	Description/ Variations of Relations	Bottom -Up	Top- Down	C	M	P	F	Des.	Prod.	Use	Retir.	
McAdams et al. 1998	3		X				X	X			X		Beverage brewers & material removal products
Newcomb et al. 1998	2	X		X		X	X					X	Automotive center console
Pimmler and Eppinger 1994	2	X	X		X	X	X				X		Automotive climate control system
Siddique et al. 1998	2	X		X			X	X		X			Automotive underbody
Siddique and Rosen 2000	2	(X)		X			X	X		X	X		Coffee maker
Stone et al. 1998	3	(X)	X		X	X	X				X		Electric screw driver
Stone and Wood 2000	3		X			X	X				X		Hot air popcorn popper
Stone et al. 2000a	3	(X)	X			X	X				X		Lignite removal system & Electric wok

Reference	**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Description/ Variations of Elements	Description/ Variations of Relations	Bottom -Up	Top-Down	C	M	P	F	Des.	Prod.	Use	Retir.	
Stone et al. 2000b	3		X			X	X	X			X		Electro-mechanical devices
Sudjianto and Otto 2001	3		X			X	X	X			X		Family of electric cordless drills
Tseng and Du 1998	1-2	(X)		X			X	X	X	X	X		Power supply switch
Tseng and Jiao 1996	1-2	(X)		X		X	X	X			X		Power supply for pulse width modulation
Tseng and Jiao 1998	1-2	(X)		X		X	X	X			X		Power supply device
Ulrich and Eppinger 2000	3	(X)	X		X	X	X	X	X	X	X		Motorcycle
Whitney 1993	1-2	(X)		X	X		X		(X)	X			Automotive-panel meter; - Radiator; - Alternator
Wilhelm 1997	1-2	X		X		X	X	X		X			Automobile
Yu et al. 1999	1-2			X		X		X			X		Toaster & Instant camera

Table 2: Modularity in the literature - management section

Reference	**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Description/ Variations of Elements	Description/ Variations of Relations	Bottom -Up	Top-Down	C	M	P	F	Des.	Prod.	Use	Retir.	
Ahmadi et al. 2001	(X)	(X)		X		X	X		X				Rocket Turbopump
Baldwin and Clark 2000		X		X		X	X		X				Computer
Baker et al. 1986		(X)		X	X		X			X			*Model*
Brusoni and Prencipe 1999	2	X		X		X	X		X	X			Aero Engines
Chesbrough and Kusunoki 1999		(X)		X			X		X				Read-Write Heads for Disc Drives
Collier 1982		(X)		X	X		X			X			*Model*
Desai et al. 2001	1-2			X	X		X	X		X			*Model*
Ernst and Kamrad 2000	1			X	X		X	X		X			*Model*
Eppinger et al. 1994	1-2	X		X	X		X		X				*Concept*
Fisher et al. 1999	1	(X)		X	X		X	X		X			*Model* & Automotive Brakes

Reference	**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Description/ Variations of Elements	Description/ Variations of Relations	Bottom -Up	Top-Down	C	M	P	F	Des.	Prod.	Use	Retir.	
Garud and Kumaraswamy 1995	1-2	X		X	X		X		(X)	X			*Concept*
Gulati and Eppinger 1996	1-2	(X)	n/a[23]	n/a		X	X		X	(X)			Automotive Control Panel
Henderson and Clark 1990	1-2	(X)		X		X	X		(X)		X		Photographic Alignment Equipment
Hyer and Wemmerlov 1984	1-2		(X)		X	X			X	X			Elevator; Agricultural machinery
Langlois and Robertson 1992	1-2			X		X	X		X	(X)	X		Hi-Fi Stereo equipment; Microcomputer
MacDuffie et al. 1996	1-2	(X)		X	X		X	X		X			Automobile assembly
Meyer and Lehnerd 1997	2-3	(X)		X	X		X	X	X	X			Electric Iron
O'Grady 1999	2	(X)		X	X	X	X		(X)	X			Computer Appliance

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[23] Exploratory paper that applies two views: from the product architecture on the organization, and from the organization on the product architecture.

Reference	**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Description/ Variations of Elements	Description/ Variations of Relations	Bottom -Up	Top-Down	C	M	P	F	Des.	Prod.	Use	Retir.	
Pine 1993	1,2	(X)		X	X	X	X		(X)	(X)	X		Lighting controls
Robertson and Ulrich 1998	1-2	(X)		X	X	X		X	X	X	X		Automotive Instrument Panel
Sako and Murray 1999	2	X		X		X	X		X	X	X		Automobile
Sanchez and Mahoney 1996	2	(X)		X		X	X		X	(X)	(X)		*Concept*
Schilling 2000	1-2	(X)		X		X	X		(X)	(X)	(X)		*Concept*
Starr 1965	1-2	(X)		X		X	X		(X)	(X)			*Concept*
Thonemann and Brandeau 2000	1	(X)		X	X		X	X		X			Automotive Wiring Harness
Ulrich 1995	3	X	X	(X)	X	X	X		(X)	X	X		*Concept;* Trailer
von Hippel 1990	2-3			X		X	X		X				*Concept*

Legend:

Systems Perspective:

Description/Variation of Elements/Modules: 1 = Module' boundaries are fixed, performance scaling only, 2 = Sub-module components can be arranged and re-arranged, 3 = Function allocation across components is wholly variable

Description/Variation of Relations/Interfaces: X = major focus of the work, (X) = implicitly considered in the work

Hierarchy Perspective:

C = component, M = Module, P = Product, F = Product Family

Life cycle Perspective:

Des. = Design Phase, Prod. = Production Phase, Use = Use Phase, Retir. = Retirement Phase

X = major focus of the work, (X) = implicitly considered in the work

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