The Multiple Faces of Modularity – A Literature Analysis of a Product Concept for Assembled Hardware Products

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Abstract

Despite the recent interest of the research community in modularity there is a lack of agreement of what exactly constitutes modularity. This has constrained empirical work on the topic, and has made the transfer of research results on modularity across disciplines difficult.

Focusing on assembled hardware products, this paper opens the black box 'modularity' and identifies the underlying assumptions and elements of modularity that are used throughout the academic literature. Instead of suggesting another definition of modularity, it identifies, analyzes, and compares usages of product modularity in the academic literature in engineering and management over the last forty years (1963-2003). For this purpose, a multi-perspective analysis tool is developed and applied to 107 individual literature references.

The analysis provides several major findings. It identifies the underlying reason why modularity is so difficult to operationalize: modularity really is a bundle of product characteristics rather than a single condition, and different views emphasize different pieces of this bundle. Further, it finds that modularity occurs at different points along the product creation process: modularity can be market-driven or technology-driven. Finally, modularity is used as a tool to pursue different objectives in different life cycle stages. As a consequence, these modularity descriptions are often incomparable. The analysis as a whole provides a vocabulary to improve communication between and within academic disciplines on product modularity, and identifies promising areas for future research.

1. Introduction

Recently, there has been a growing interest in modularity – both in industry and academia. In industrial practice, examples of recent products that claim to be modular - beyond the ubiquitous example of the personal computer - 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 today delivered as modules.

Similarly, recent academic publications have identified various advantages of modularity in individual areas. For example, 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). The number of recent academic publications on product modularity indicates the relevance of the topic in a variety of research fields. Plotting all sources (107) identified for this paper by publishing date reveals that the interest in product modularity has experienced a significant growth over the last decade (Figure 1).[1]

Figure 1 about here

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[1] The reason for the decline in the number of publications in the last year of the data set (2002) is as of yet unclear. It might be just an anomaly in the longer trend in the data; alternatively, it might signal that this research topic has been exhausted.

The multitude of academic research projects concerned with modularity has produced many interesting results. However, this widespread interest has also produced a number of different ways to describe and define modularity, which are often similar, sometimes overlapping, yet slightly different. For example, some sources focus on technical function containment as the characteristic module feature, for others the option for the user to be able to reconfigure the modules, and thus the product, is the key point of modularity, and yet others emphasize complexity reduction during assembly as representative feature of modularity. But what then is modularity? Are there different levels of modularity? Can products be more or less modular? Does a product consisting of 'modules' exhibit 'modularity'? And if so, what determines a 'module'?

These questions are relevant beyond a pure theoretical discussion for a number of reasons. The overlapping yet often slightly different descriptions and definitions of modularity have made it very difficult to empirically test modularity's development, its causes, or its consequences. In fact, this lack of modularity's operationalizability is likely to explain why there are very few empirical studies on modularity. Also, the gap between how product modularity is used in a conceptual way in some disciplines, and how it is described in technical details in others, hinders potentially beneficial cooperation between these disciplines. For example, it is very difficult to translate conceptual or strategic findings on modularity in one field into concrete product design advice in another.

This paper does not attempt to add yet another definition of modularity in the hope it will be the ultimate one. In contrast, this analysis opens the black box 'modularity' and identifies the underlying assumptions and elements of modularity that are used throughout the academic literature. To extract the essence of modularity, i.e., to find the elements that are common across disciplines and to improve the understanding of the remaining differences, I develop a multi-perspective analysis tool and apply it to each individual literature reference. The analysis results help explain how the different definitions and viewpoints relate to each other. They illustrate that modularity really is a bundle of product characteristics, and different views emphasize different pieces of this bundle.

The contribution of this paper is threefold. First, it identifies over 100 references concerned with research on product modularity, covering over 40 academic journals, books, book sections and conference proceedings from 40 years of academic research. Second, the development of the analysis framework, grounded in observations and theoretical considerations, and the analysis itself contribute to bridge disciplines to improve communication between them and support cooperation efforts. Third, building on the insights of the analysis I identify avenues for further research.

Two boundaries determine the scope of this paper. The first boundary is defined by the subject of the analysis. This literature analysis 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. For example, software design allows to construct hierarchies that are impossible in the physical world. Therefore, this paper restricts the scope of the analysis to hardware products. The second 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, 2003), the analysis here - due to its focus on assembled hardware products - centers on the literature bodies in engineering and management.

The remainder of this paper is organized as follows. Section 2 presents the methodology for the analysis. It presents the procedure for identifying the 107 references, and explains the development of the analysis framework. Sections 3 through 5 contain the individual analyses of the selected literature body through the three lenses *systems, process*, and *life cycle*. Section 6 integrates the analyses results and concludes with identifying opportunities for further research.

2. Methodology

2.1 The data: product modularity in the engineering and management literature from 1963 to 2002

Over 100 articles, papers, books, and book sections serve as the data material for this analysis. In order to assemble a comprehensive list of definitions, interpretations, and usages of modularity, an extensive five-step search was conducted. The first step identified 34 academic journals, spanning both engineering and management fields (Table 3). More specifically, due to the focus on hardware products, in the engineering field the emphasis was placed on literature in design engineering and manufacturing. The coverage of the management field ranges from management of technology, to operations research, to industry and business analysis. While this list of journals does not claim to be perfectly exhaustive, it represents a selection that I feel can be understood as representative for the current state of research on product modularity.

Table 3 about here

In the second step, I conducted a search in all 34 journals, using the ISI Web of Science database which includes the Science Citation Index, the Social Science Citation Index, and the Arts and Humanities Citation Index. The search covered the last forty years (1963 – 2002).[2] As search term I used ‘modul*’ to ensure that in addition to the term ‘modularity’ also terms like ‘module,’ ‘modular,’ and ‘modularization’ were captured in title, keywords, or abstract of the articles. The initial search resulted in a list of 487 articles.

Third, all articles that were not relevant to product modularity were removed. The wide cast search net returned also a large number of false positives like ‘signal modulation,’ or ‘modulated Petri Nets.’ To maintain the focus of this work on modularity of complex hardware products I developed and applied rules to exclude non-relevant articles from the initial list. For example, 14 articles whose sole focus was on modularity of organizations were removed. They included works that focus on modularity of firm capabilities (e.g., Kusunoki et al., 1998), on modular organizational forms (e.g., Schilling and Steensma, 2001), or on modular production networks (e.g., Sturgeon, 2002). 310 articles were excluded from the search list because they reported on modules of software, algorithms, or procedures. These range from articles proposing optimization models for quality and cost for modular software (e.g., Jung and Choi, 1999) to articles developing parallel algorithms for modules of learning automata (e.g., Thathachar and Arvind, 1998). 93 articles were dropped because their central focus of modularity was non-hardware product related. For example, research on innovation that focuses more on the interdependence of knowledge streams than product modularity per se (e.g., Fleming and Sorenson, 2001a, 2001b) remains outside the scope of this analysis, as does research on digital

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[2] In some cases, the ISI Web of Science database coverage reaches back to 1945. However, the earliest entry the search returned was 1963

forms of modularity (e.g., Majumdar, 1997). 4 articles were removed from the list because the search term ‘modul*’ caught them although their content has nothing do with modularity. For example, one paper appeared in the search list because it reports on bonding high-*modul*us composites for a machine tool structure (e.g., Suh and Lee, 2002). Finally, 5 articles remained unconsidered because they were book reviews (of books represented elsewhere in the list), and 8 articles were removed because the list contained already similar works by the same author(s). After manually eliminating these non-relevant articles from the list, the remaining data set comprised 53 articles.

In a fourth step, the data set was augmented by two groups of works that elude a ‘modul*’ search in journal databases. The first group concerns publications outside of academic journals. Several conference papers, books, and book sections that were widely known and cited in the research community that works on modularity issues were added to the data set from the original search. The second group attempts to cover sources that are located in fields adjacent to modularity such as variety, standardization, and product platforms, but are predominantly concerned with product modularity. The final list comprises 107 entries.

The final step of the procedure split the list into two lists, one labeled ‘engineering,’ the other ‘management.’ This splitting was conducted on the source level, not on the level of the individual article.[3] For example, I first coded all journals as belonging to either one of the two lists. Next, all entries were assigned to one of the two lists depending on the code the journal in which they appeared had received. The idea behind this split is to investigate whether the disciplinary origin of a research paper or article matters in the way ‘modularity’ is used and

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[3] For obvious reasons, the entries in the list that are books were assigned to the two lists directly.

applied. Table 4 presents the results of the journal coding procedure as well as the resulting coding of the articles, papers, and books.

Table 4 about here

2.2 The analysis tool: 3-perspective framework

Comparing the multiple ways modularity is defined and used in research efforts of various academic disciplines reveals that the definitions are often similar yet not identical. Some of these differences follow disciplinary lines, others cut across them.

For example, considering the detail of description of modularity, some of the more management oriented literature describes modularity on a relatively abstract level as having ‘standardized’ and ‘interchangeable’ components, while some of the literature rooted in engineering provides detailed specifications, such as the physical nature of an interface or that it ‘must allow non-destructive separation.’ At the same time, one can find in both the management and the engineering literature sets uses of modularity that exhibit very detailed descriptions of functional interactions, geometric locations, or innovation potential; just as descriptions are present in both sets that, for example, simply assume that components are perfectly interchangeable in order to focus on modularity as a combinatorial problem.

Looking at product development processes, other differences in the use of modularity - both along discipline lines and across them - concern the point in time when the modularization occurs in the product creation process. Sometimes, the decision to form modules can be observed in the middle of the design stage where technical decisions are made. In contrast, in other cases the modularization process is controlled by market segmentation decisions.

Although by its very nature literature from the engineering discipline can be expected to populate more the technical arena and literature from the management discipline to be found more in the market arena, both sets also contain examples of modularity occurrence points that are otherwise typical for the other set, respectively.

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 (‘can be designed independently but functions as a whole’), for others the efficient organization of production or distribution (‘can be manufactured and assembled independently’). Yet others see the advantage of modularity in that it allows the customer to re-configure her product (‘customer’s choice to mix-and-match components’), and again others suggest modularity to make products easier to recycle. Again, there is no clear separation between the disciplines regarding these viewpoints.

Apparently, the ways in which the topic modularity has been researched, defined, and applied, exhibit - in addition to disciplinary idiosyncrasies - a number of characteristics that cut across discipline lines. How can all these different viewpoints be reconciled? Is there a way to improve the coherence of the understanding with respect to modularity within the different thought worlds, and simultaneously to bridge the gaps between them?

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 developed to distill the common aspects of modularity and to understand the conditions under which additional, perspective-specific aspects occur. Three perspectives represent the lenses through which the often overlapping yet still slightly different modularity descriptions can be investigated (Figure 2).

The first perspective focuses on how modularity is described. Analogous to a system, every product can be described through its elements and the relations between them. From this perspective, each article is analyzed as to how elements and relations are described to determine modularity. This view is labeled ‘systems perspective.’ The second perspective investigates the point of occurrence of modularity in the product creation process. Modules based on functionality from a technical viewpoint can differ considerably from those defined from a market viewpoint. This view is named ‘process perspective.’ The third perspective explores how the choice of one phase of the product life cycle over another can result in emphasizing some aspects of modularity while pushing others to the background. This third view is the ‘life cycle perspective.’

Figure 2 about here

Note that in contrast to other literature reviews that cover an entire field of research (see, for example, Finger and Dixon, 1989a, 1989b, for an extensive review of research in mechanical engineering design) or a field of application (see, for example, Krishnan and Ulrich, 2001, for a comprehensive review on literature relevant for product development), the analysis presented here is guided by a phenomenon, i.e., modularity. Consequently, this framework does not cluster the literature into permanent, overall groups but uses instead the different perspectives of the framework as lenses through which to analyze each individual reference.[4] While *within* each of three perspectives the analysis results in groupings of the literature, these groupings are not identical *across* the different perspectives. The following three sections analyze modularity from three perspectives: systems, process, and life cycle.

3. Systems perspective: do modules or interfaces determine modularity?

Trying to capture what modularity is, or how the term is used by various scholars and practitioners, leads quickly to the notions of modules and interfaces, i.e., dependencies between them. This is illustrated by an often encountered notion of modularity that describes modules as exhibiting relatively weak interdependencies between each other and relatively strong interdependencies within them (e.g. Alexander, 1964, Ulrich, 1995, Baldwin and Clark, 2000, Schilling, 2000).

However, the attempt to operationalize this conceptually powerful but somewhat generic notion leads to a number of additional questions. For example, if the level of interdependence of a subunit is a pre-condition to become a module, then do different levels of interdependencies represent different levels of modularity? And what determines these different levels of interdependence – their number, their ‘strength,’ their physical quality?

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[4] The analysis results in 321 data points (3 perspectives times 107 references). While the discussion in the text uses examples to illustrate the findings, the tables in the appendix provide all detailed results. In addition to the complete analysis details, the tables in the appendix also present the hardware product that was the focus of each individual reference.

Alternatively, what role do the modules play in determining modularity? Is the level of modularity affected by the modules' own characteristics, i.e., their size, function, or role within the product? And if modules are a precondition for modularity, are products with more modules more modular than products with fewer modules?

To approach these questions, I borrow from the systems literature to construct the first lens of the analysis framework. In the systems engineering literature, a system is determined by its elements and the relations between these elements (e.g., Maier and Rechtin, 2000). Adapting this view, there are two fundamental dimensions which most product descriptions and analyses employ: (1) the elements the product consists of and (2) the relations (i.e. interfaces) between these elements (Figure 3). These two dimensions span the area onto which I map the literature from the systems perspective. Below the two dimensions are described in more detail, followed by the assessment of how different references have used and interpreted modularity along these dimensions in different ways.

Figure 3 about here

3.1 Elements: a product's modules

Determining what a module is requires the decomposition of a product into sub-units. Often, this process attempts to align the product's functional requirements with its physical components. On a conceptual level the idea of product 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 to describe modules. These approaches cluster into three sub-groups, which can be distinguished by the extent to which they consider architectural changes in the way functions are allocated to the product's elements (Figure 4). In the simplest case, I term 'parametric,' the elements' functional boundaries are fixed and only predetermined sub-units can be exchanged. The second case, labeled 'configuration,' 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 4 about here

3.1.1 Parametric approach

With respect to modularity, this approach is labeled 'parametric' because it considers the product structure as essentially fixed, and product characteristics are varied only within the boundaries of the individual elements. In other words, only one (or a few) design parameter(s) are changed (parameterized) while all others remain constant. This approach can be stylized by the exchange of one sub-unit by another one which exhibits different characteristics (see the replacement of A4 by B4 in Figure 4). Examples are color changes of face-plates at cell phones, or the use of different power sources in otherwise identical products, e.g., power tools. This approach has not only been pursued to produce product variety, but also to minimize environmental impact. For example, Coulter et al. 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 (in this case: a 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, or consistently contribute to, the function or feature that is to be changed (or varied).

The parametric approach can also often be found in the operations management and operations research world. For instance, models developed to identify potential gains from parts commonality implicitly assume that different products work individually as intended even if they use common subunits.[5] Using this simplification, some models investigate how parts commonality affects safety stock levels (Collier, 1982, Baker et al., 1986), how parts commonality affects supply chain costs (Ernst and Kamrad, 2000), or how matching supply chain structure to variety type affects firm performance (Randall and Ulrich, 2001).[6] 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[7], the analyses focus on balancing cost penalties from overdesign with cost savings from commonality. For example, Fisher et al. (1999) investigate

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[5] In addition, they assume interfaces that guarantee total interchangeability of components or modules. This aspect of modularity is discussed in section 3.2.

[6] Randall and Ulrich distinguish two types of variety: production-dominant variety and mediation-dominant variety. In case of the former the increase of production costs associated with increased variety outweighs the increase in market mediation costs, in case of the latter vice versa. In either case, however, the variety is provided by a change in an attribute. Their case products, bicycles, have four attributes: frame material, frame geometry/size, frame color, and components. As a consequence, the product architecture does not change an ‘exchange’ of an element with an element with a different attribute level.

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

the factors that determine the number of different brakes across a car family, and Thonemann and Brandeau (2000) develop algorithms to find the optimal level of commonality for automotive wiring harnesses. For components whose quality level does impact product quality, Desai et al. (2001) model how to balance the revenue and cost effects of commonality for the different quality levels of the components.[8]

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.[9]

Other approaches that belong to the group treating modules as differing only in quality can be found in design optimization. For example, Nelson et al. (2001) use multicriteria optimization techniques to investigate the performance degradation through the use of common parts (modules) in a product family. Similarly, Hernandez et al. (2001) develop a method with which

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[8] 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.

[9] While group technology strives for commonality along these different dimensions, their effect on commonality from a functional perspective may vary. For example, if a common manufacturing process is the goal, the part function is of only secondary concern. I am thankful to Dan Whitney to pointing this out.

they estimate the cost and time impact in production that a commonization of components across a product family would deliver. For the case of common components that differ with respect to their reliability forming the modules, Hwang and Rothblum have developed a procedure that can find optimal assemblies (1994).

In sum, characteristic feature of the parametric approach with respect to modularity is that the product architecture is assumed fixed and product features are varied only within the boundaries of the elements (e.g., material, quality, color, etc.). Implicitly assumed is that the replacement must not compromise overall product function.

3.1.2 Configuration approach

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 (and re-arranging) these components into larger units (A2+A4 or A2', configuration case in Figure 4). 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 for which the expected innovation rates of the underlying technology differ across components, it has been suggested to group components with similar innovation rates into modules (Martin and Ishii, 2000). Others have focused on improvements of the product development process (Ahmadi et al., 2001) or the product's end-of-life environmental performance (Newcomb et al., 1998) as criteria driving the module formation process. A major tool developed to help in this module formation process is the interaction matrix and its various derivatives.[10] Some matrices document interactions of the associated development processes (Eppinger et al., 1994), others indicate the components' levels of suitability to belong to one and the same module along multiple criteria (Huang and Kusiak, 1998). In most cases, in the process of modularization columns and rows are re-arranged to minimize unwanted interactions or to increase the desired 'similarity.' Genetic algorithms have also been suggested for this clustering process (Gu et al., 1997).

Some of the earliest articles in the analyzed list belong to the configuration approach. Starting with Evans forty years ago (1963), who introduced the problem of optimizing assortments under the name 'modular design,' several researchers from the operations research community have tackled this problem using a configuration approach (e.g., Shaftel, 1971, Shaftel and Thompson, 1977, Goldberg and Zhu, 1989, Goldberg, 1991).

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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 (low-level) Schedule DSM (Browning, 2001). 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). Groups (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 ‘configuration’ approach is also used in works that develop an inventory of basic modular units that allow the user to configure a modular robot (Cohen et al., 1992), or to match a product family architecture with multiple customer groups (Tseng and Jiao, 1998).

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 to pre-set criteria. Although module boundaries vary according to the different criteria, the goal, in general, is to (a) group ‘similar’ elements and (b) to transform interactions between modules into interaction within modules.

3.1.3 Fundamental approach

While the second approach is constrained by the pre-definition of sub-module level components, the third approach 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 4). As an illustration, consider the example of a computer. The configuration 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’).

“The scheme by which the function of a product is allocated to its physical components” has been described as the product architecture (Ulrich, 1995). 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)

Several sources suggest ways to operationalize the concept of allocating product functions to components. 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. (1999) compare different products to identify possible common modules. 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. (2001) compare function structures for common and unique functions across a product family to define possible product architectures. These approaches offer some unique challenges. For example, how are functions compared with each other? Currently, most researchers use some sort of weighting scheme (e.g. Mattson and Magleby, 2001, Kamrani and Salhieh, 2002). Research work that proposes optimization procedures or design guidelines often recommends interdepartmental negotiations to agree on these weights (e.g., Gonzalez-Zugasti et al., 2000).

Compared to the ‘configuration’ sub-group, this ‘fundamental’ sub-group uses a higher level of abstraction (physical functions 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 approaches.

3.2 Relations: A product’s interfaces

The extent to which the relations between a product’s elements, i.e., its interfaces, are described in the modularity literature relevant to product modularity varies significantly. The differences are both of qualitative and quantitative nature. For the purpose of the analysis presented here three levels of description detail have been defined.

3.2.1 Low level of detail

The category that exhibits a low level of detail in its interface description includes papers that typically assume that whatever the role of the interface for the product function is, it is not impacted by the choice of modules and components. This is often the case for optimization procedures using the parametric or configuration approaches (e.g., Kim and Chhajed, 2000, Chakravarty and Balakrishnan, 2001, Krishnan and Gupta, 2001, Lee and Tang, 1997). Similarly, of those works that focus more on the aspects of designing and producing the product, some also do not mention explicitly specific characteristics of the product’s interfaces (e.g., He and Kusiak, 1998, Stone et al., 1998).

While - in the context of modularity - conditions that allow some sort of interchangeability are often implied, the works in this category exhibit a low level of detail in their interface descriptions.

3.2.2 Medium level of detail

The category that shows a medium level of detail encompasses two subgroups. The first of these subgroups indicates the required interchangeability with a general notion of 'standardization.' In fact, in some cases interface standardization becomes the factor that determines product modularity: "Production of components conforming to standard interface specifications also leads to modularity." (Garud and Kumaraswamy, 1995, p.94) or "a modular product architecture [..] is a special form of product design that uses standardized interfaces 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).

Some practitioners also use module definitions that imply a certain level of interface standardization to conduct work on the components (modules) separately. For example, according to Wilhelm (1997), 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."

The second sub-group consists of references that advocate the use of interface counts for modularity specifications. For example, Allen and Carlsson-Skalak (1998) suggest as a modularity measure the ratio of number of inter-module interactions to the number of modules, and Mattson and Magleby (2001) propose a ratio of number of existing interfaces used to number of total interfaces used.

In sum, this second subgroup is more explicit about the conditions considered important for modularity than the first one, but it does not describe interfaces qualitatively.

3.2.3 High level of detail

There are two ways in which a source can exhibit a high level of detail in interface description. First, it requires to measure the 'strength' of an individual interface. This measure is supposed to indicate distinguishable levels of dependence of the participating components forming the interface under consideration. One example of such a 'strength measure' is a dependency measure suggested by Martin and Ishii (2000, 2002). To support product family development, they suggest to measure - in addition to the innovation rates of components (both technology and market driven) and thus their likelihood to change - the extent to which changes in one component trickle through the rest of the product.

The second possibility in which a source can demonstrate a high level of detail in its interface description is by requiring to describe the physical nature of an interface. In other words, it is relevant whether the interface is transmitting mechanical forces, electrical current, material, or information; and whether it is a contact or no-contact information (Pimmler and Eppinger, 1994, Ulrich, 1995, Erixon et al., 1996). In addition to describing the interface's nature, most of these authors add a qualitative measure of strength or desirability.

Overall, interface descriptions on a high level of detail exhibit a fair amount of detail, ranging from quantitative dependency measures to categorizing the physical nature of it.

3.3 Comparing elements and relations: systems perspective

Figure 5 summarizes the findings of the literature analysis through the lens of the systems perspective. The figure provides two major insights. First, taken as a whole, the analyzed literature covers the whole range of possible locations along the two dimensions 'elements' and 'relations.' Although the regions with one value very high and the other very low are somewhat thinner populated, there is no general significant clustering. The deeper insight of this is that within the literature body analyzed, a variety of different modularity descriptions is in use.

Figure 5 about here

The second insight is revealed if the analysis results are considered separately for the literature subsets coded as 'engineering' and 'management.' Although both groups are represented in almost every field of Figure 5, if the sum of the entries of each column and each row are compared, a difference in emphasis between these two research communities emerges (Figure 6). While the majority of the articles coded as 'management' employ the parametric version of the element description, i.e., they focus on the interchangeability of modules without detailing its mechanisms, those coded 'engineering' tend to cluster more around the configurational approach. Also, the engineering literature's representation in the 'fundamental' category of design descriptions is much stronger than the one of the management literature.

With respect to the consideration of detail in its interface descriptions, both sections of the literature exhibit very similar distributions. Both are most strongly represented in the low-detail area, and show decreasing numbers with increasing levels of details.

Figure 6 about here

4. Process perspective: when (and where) does modularity occur?

Investigating how modularity is described along the dimensions elements and relations is one way to understand how modularity is used in the literature. Another is to examine where modularity comes from in the individual references. In some articles modularity follows from the identification of user needs for variety, in others modularity is the result of a search for potential common technical functions.

To search for the origin of modularity means to look for its occurrence along the product creation process. In other words, when are decisions made to create a modular product. Fundamentally, most industrially developed and manufactured hardware products that are targeted to anonymous mass markets follow a similar path through their creation process. First, market research studies are conducted to solicit customer needs and wants. Next, the market requirements are translated into technical product specifications and designers develop and select technical solutions in the product design phase. Finally, the product information is used to manufacture its components and to assemble them into the finished product.

Modularity tends to occur at one of two different points in time during this product creation process. The first point in time is located towards the end of the market research phase, the second one can be found in the product design phase (Figure 7). I will discuss both in greater detail below.

Figure 7 about here

While the main question of this section's inquiry is focused on the time aspect of the modularity occurrence, i.e., *when* does it occur, there is a second aspect that describes the modularity occurrence on a product hierarchy level, i.e., *where* does it occur. A detailed analysis of the modularity occurrence with respect to the hierarchy level for all articles complements the analysis of the time aspect of the modularity occurrence.

4.1 When does modularity occur: Technology-driven modularity and market-driven modularity

There are two major possibilities when modularization can occur in the product creation process. One possibility is that towards the end of the market research phase the mapping of product features to various market segments leads to the modularization of the product. In other words, the results of the market research phase are variety needs that are converted into product requirements. An example is the requirement to offer a product in multiple colors.

Alternatively, the modularization can occur during the product design phase. During product design, engineers break down complex problems into simpler ones, solve those, and synthesize the overall solution. During the problem solving process opportunities for modularization can become visible and designers may pursue them. For example, if several product functions can be provided using hydraulics, the engineer might decide to create a hydraulic module.

4.1.1 Market-driven modularity: how markets are served

Researchers in the market-driven modularity category typically 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 (Figure 8). 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 reasons, i.e., to strive for commonality. The fundamental question is how to translate different customer needs and expectations into product (family) architectures. In case of the market-driven modularity occurrence, this translation takes place *before* the product design phase.

Figure 8 about here

The way the variation of customer needs is treated is key for this mapping from customer needs to product architectures. Some articles 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, some have focused on the extent to which an existing product family accomplishes the use of common parts and components. Kota and colleagues, 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. (1996) have developed composite variables that reflect, among other things, levels of parts commonality. 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 and colleagues develop a product family reasoning system that identifies candidate sets of platforms out of a set of existing products, subject 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. (1999) suggest a customer need analysis that represents customer need target values as probability distributions across market segments and over time. 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, some suggest 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). Similarly, the configuration approaches that pursue the optimal combinations of components to serve a given market variety fall in this market-driven category (e.g., Baker et al., 1986, Collier, 1982, Goldberg and Zhu, 1989, Goldberg, 1991).

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.

In sum, the articles in the market-driven modularity category begin with the understanding of a need for product variety, suggest methods to identify commonality on various levels of product family, product, and components, and argue for balancing the two.

4.1.2 Technology-driven modularity: how engineers design products

While the marketing perspective sees a product as "a bundle of attributes," engineers view a product as "a complex assembly of interacting components" (Krishnan and Ulrich, 2001, p.3). Design engineering in product development can be understood as a sequence in which analysis is followed by synthesis. The mental framework of this approach is rooted in the engineering world. Engineers are trained and educated to break up problems that are too complex into smaller ones until they become manageable. In other words, complex problems are analyzed and divided into smaller sub-problems, which then are analyzed and divided further into individual problems. For these individual problems, the designer finds solutions and synthesizes (aggregates) them into sub-solutions, which in turn are joined to form the overall solution for the product or system (Figure 9).

Figure 9 about here

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,[11] (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.

Having defined functions on these fundamental levels, engineers ‘assemble,’ i.e., synthesize, 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.[12] 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.,

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[11] 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).

[12] Dominant flow refers to the highest ranking (from customer needs) non-branching flow (e.g. the specimen in Figure 6), 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.

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 map functions onto physical components (e.g., Erens and Verhulst, 1997). Others apply the idea that components exhibit various levels of 'suitability' with respect to belonging to a certain module (e.g., Karmarkar and Kubat, 1987, Huang and Kusiak, 1998, Tsai and Wang, 1999). Not surprisingly, sources that describe the details of the design process also fall in this technology-driven modularity category (e.g., Ulrich and Eppinger, 2000, Kamrani and Salhieh, 2002).

The characteristic common to all references in the technology-driven modularity occurrence category is a detailed study of the product's technical functionality, followed by an assignment of functions or set of functions to physical elements. Finally, elements are combined into complete products or product families. The module formation process, and therefore the modularity definition, takes place at a technically detailed level within the product design process.

4.2 Where does modularity occur: Product hierarchy

The second dimension of the process perspective is concerned with the product hierarchy, in which modularity can occur at different levels.

More than four decades ago, Herbert Simon noted that complex systems tend to organize themselves in hierarchies (Simon, 1962).[13] Others have found that almost all products are part of 'nested hierarchies,' i.e., while exhibiting an internal hierarchy they are simultaneously part of an

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[13] 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)

upper-level hierarchy (e.g. Christensen, 1992a, Gulati and Eppinger, 1996, Baldwin and Clark, 2000, Schilling, 2000).

All assembled hardware products exhibit a product hierarchy. Another way of representing nested hierarchies is that a product hierarchy comprises various levels, and the complexity of the units increases with higher levels of aggregation. For example, the lowest level of a product hierarchy might exhibit individual components, parts, etc. On the next higher level of the product hierarchy more complex units such as subassemblies can be found. The next level up may correspond to an entire product, and yet another level up might represent a product family.

Researchers describing, defining, using, or recommending modularity have applied all of these levels in their work on modularity. Some argue to understand the simplest elements, i.e., components as modules to approach a ‘mix-and-match’ solution. Others pursue modularity by grouping components into modules, for example to restructure assembly processes. Yet others view modularity from the perspective of the product family, i.e., multiple instances or generations of similar products.

While most articles exhibit some focus along this hierarchy dimension, the majority of papers considers more than just one level. Consequently, the paper’s uses of modularity cover in most cases two, sometimes three levels of the product hierarchy.

4.3 Comparing product creation process and product hierarchy: process perspective

The results from analyzing the literature through the process lens are recapitulated in Figure 10. Taken as a whole, the selected articles cover the entire spectrum of both dimensions, i.e., the time and the hierarchy aspect of the modularity occurrence. The location of each article with respect to the product creation process phase in which modularity occurs is unambiguous, i.e., each paper appears either in one category or the other, but not in both. In contrast, and as mentioned above, with respect to the product hierarchy, most articles are represented in more than category (e.g., article 2's use of modularity includes two hierarchy levels: *module* and *product*).[14] The entire set of references is split about 1/3 to 2/3 between the technology-driven and the market-driven modularity occurrences. Along the product hierarchy dimension the score covers all hierarchy levels with the following distribution: component (1/6), module (1/3), product (1/3), and product families (1/6).

Figure 10 about here

A closer look at the analysis results separated in the engineering and the management set reveals another insight. While the distribution along the product hierarchy dimension is almost identical for both sets, the difference between them with respect to how they fall into the technology-driven and market–driven categories is remarkable (Figure 11). The references coded as 'engineering' split evenly between the two modularity occurrence categories. In contrast, the vast majority of the references labeled 'management' (83%) are located in the market-driven modularity category. Apparently, the engineering literature has worked its way upwards the product development process path towards market research more than the management literature has its way downwards to detailed product design.

Figure 11 about here

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[14] On average, each article is placed in 2.33 categories along the product hierarchy (249 scores, 107 references). To distinguish these multiple representations I use the term 'score,' instead of 'count.'

5. Life cycle perspective: modularity for whom?

The third perspective for this analysis focuses on various phases over a product's life time. Every product runs through four major phases in its life[15] and each life cycle phase comprises multiple different activities (Figure 12). Numerous approaches have been developed to optimize products for a variety of these activities (e.g., see some illustrations of the DFX literature in Figure 12). Similarly, a number of different ways to describe the 'optimal modularity' for specific life cycle phases or activities can be found in the literature. Some pursue the modules that optimize the product development process, others suggests modules that allow component risk pooling for inventory reduction, and again others call for modules with similar materials to facilitate recycling. As a consequence, the individual module definitions across these references are very different.

To investigate the life cycle focus of each article, the third lens, the life cycle perspective is applied to the whole data set. The analysis below details the findings, structured along the individual phases.

Figure 12 about here

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[15] Note that the term *product life cycle* is used here to describe the phases individual products go through. This is in contrast to the use of the term describing a life cycle of a product concept, which occurs, for example, in the discussion on dominant designs. There the life cycle describes phases through which a concept emerges, solidifies, and matures.

5.1 Design and Development

Researchers interested in design and development (D&D) processes are typically concerned with the question of how to improve process performance of D&D, i.e., how to reduce resource consumption (cost) and to shorten time requirements, condition to a certain level of product functionality and quality. Since many of 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, teams, and organizations. Organizational structures tend to mirror the structure of the products the organization makes (Henderson and Clark, 1990). The organizational structures in turn determine the need for communication and coordination, and efficient communication and coordination maximize resource productivity. Thus, the question is: what are the structural characteristics of a product that minimize the resources required to develop it?[16] In other words, what are the modules (number, size, location, etc.) and interfaces that best facilitate the product development?

Researchers have proposed methods that 'modularize' the product, and in turn 'partition' 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 conducted than a task that has a high degree of interdependence with other

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[16] This mapping from product structure to design and development effort is a somewhat simplified representation. Some have suggested that there actually is a two-way relationship between product architecture and organizational design (Gulati and Eppinger, 1996). Also, in addition to the product architecture, organizational decisions alone, like sequential iteration or overlapping, influence the efficiency of development processes (e.g., Smith and Eppinger, 1997b, Krishnan et al., 1997). For the purpose of this analysis, however, I focus on the effect product architecture/modularity have on the organizational performance with respect to product development.

tasks (von Hippel, 1990). For the case of testing, Loch et al. show how a modular architecture can lower the testing costs “because it allows parallel testing without an increase in the number of test combinations (2001, p. 674). Other researchers, based on the design structure matrix (Steward, 1981), have developed several modeling techniques to predict the impact of product architecture choices via organizational structure on development time and cost (e.g., Eppinger et al., 1994, Ahmadi et al., 2001). In general, module definitions in these works aim at minimizing the communication effort and at reducing the risk level within larger development efforts.[17]

In addition to the resources required to work on the individual project chunks, i.e., modules, extra resources are required to integrate the modules and components into a complex product. Some argue that a firm needs to ‘know more than it produces’ because complex systems require extra knowledge for integration (Brusoni and Prencipe, 2001). Others argue that extra integrative capability is necessary to help the organization avoid being trapped in case innovations cause architectural shifts. Chesbrough and Kusunoki make this case with data from the disc drive head industry (1999). This notion has been cautioned, however, for industries whose products exhibit stable component interfaces, such as bicycles (Galvin, 1999).

5.2 Production

This phase includes all process steps a product goes through during its physical construction, i.e., component fabrication, assembly, and logistics with purchasing and inventory.

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[17] Individual studies employing DSMs often search for an optimal way to organize product development for a given product architecture. Taken together, however, they point out differences in product architectures that allow, or hinder, efficient product development processes.

If one understands the use of common components across multiple products as modularity, then the idea of a simplifying concept in the world of parts fabrication is already a century old. What Henry Ford accomplished for components *within* a single product series (standardized parts), was proposed by an automotive engineer already in 1914 *across* product series: standardized wheel sizes, hubs, bearings, 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 the use of few components across many products. 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. For low volume, high variety products, Salvador et al. propose combinatorial modularity as a special case of ‘slot modularity’ (2002). Examples in the literature for the use of common components across product families in production are panel meters (Whitney, 1993) and wiring harnesses (Thonemann and Brandeau, 2000). Studying the home appliance industry, Worren et al. measure product modularity by the extent of component reuse and the degree of component carry-over (2002). What all these definitions implicitly determine are some features of the modules: they represent common components with a limited number of interfaces.

In production, sometime ‘modules’ are also understood as assembly modules. Typical characteristic of assembly modules is that they form collections of components that can be separately assembled and tested. These preassemblies enable to restructure and simplify the assembly work path. This restructuring effect of work can be observed particularly at complex, assembly-intensive products such as automobiles (Wilhelm, 1997), or machines, e.g., assembly stations (Kohlhase and Birkhofer, 1996).

Another argument for modularity is sometimes made with respect to logistics. The literature promoting late customization or postponement strategies to reduce inventory and shorten lead times often advocates modularity: “A product with a modular design provides a supply network with the flexibility that it requires to customize a product quickly and inexpensive.” (Feitzinger and Lee, 1997, p.117). In other words, the cost of creating variety are dependent on the point in the production process where the variety occurs (Ishii et al., 1995). With customers indifferent to higher quality components, risk-pooling can reduce required overall inventory levels (Weng, 1999). However, to achieve the desired late customization may require to change the sequence of production processes for a product (Lee and Tang, 1997).

In sum, most module definitions concerned with the product’s production phase aim at lowering production and logistics costs, and at reducing lead times. Major ideas behind this are economies of scale for common 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 and Operation

The set of references that considers a product’s use and operation encompasses two groups. First, many articles use implicitly the use phase in their argument for modularity. The reason is that their use of modularity builds on the product’s functionality, i.e., the function the product will perform while it is in use or operation. Many module definitions that originate in the engineering world follow this idea (e.g., Jiao and Tseng, 1999, Joneja and Lee, 1998, Sharman et al., 2002). For example, if motor power is a distinguishing characteristic for different products in a product family, than the function ‘propulsion’ might be considered as a candidate to be contained in a module.

The second group takes into account various causes for variety or change during the product’s use phase. Causes range from enabling the user to configure his product by mixing and matching predetermined elements to allowing cost effective configuration. An example of the mix-and-match idea is today’s stereo equipment (e.g., Langlois and Robertson, 1992). Ulrich (1995) discusses additional opportunities that can provide customer value through variety: upgrades (e.g., more powerful computer chip), add-ons (e.g., extra memory chip), and adaptations (e.g., allows product use with 110 or 220 Volt). A special case of the adaptation problem is the planning of modular fixtures, where the set of different products that a fixture should secure determines the required variation of the fixture over time (Lin and Huang, 2000).

In one of the few empirical works on modularity, Duray et al. (2000) measure product modularity indirectly by assessing whether the customer can order end-user specified components and whether these customized products still have interchangeable features, i.e., common parts.

Many assembled products are durable goods and subject to repair and maintenance. As such, different rates of wear and tear for various components make a grouping, i.e., modularization, along these parameters an attractive solution. For example, Dahmus and Otto (2001) argue for considering failure probability and replacement cost as factors when drawing module boundaries, and Karmarkar and Kubat, 1987 develop an analytical model for the same purpose.

In general, most concepts underlying modularity during the use and operation phase are similar to those during the production phase, although some differ. The similarity is due to the fact that some of the issues when mixing-and-matching components in the use phase are alike issues during assembly. Dissimilarities processes occur only once during production but multiple times during use. An example is an irreversible assembly process (e.g., welding) that does not allow an easy disassembly for, say, maintenance.

5.4 Retirement

The final phase of a product's life is its retirement. Apart from being dumped on the landfill, two major paths exist for the product after its initial use phase, depending on the post life intent. First, it could be refurbished as a unit or its components could serve as spare parts, and second, the product (or parts of it) could be transformed into other use. For assembled products, the former always includes 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 post-life 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 Coulter et al. change materials, but not the modules' boundaries. Others suggest modeling the cost of recycling, disassembly, shredding, and dumping to support the decision of placing module boundaries (Zhang et al., 2001). Finally, some suggest to combine post-life requirements with functional requirements to structure the product (e.g., Kimura et al., 2001, Sand et al., 2001).

In sum, the requirements of a post-use phase can be very similar (e.g., disassembly) or very different (e.g., material recycling) from those in design, production, or use. As a result, module definitions can differ considerably.

5.5 Comparing design, production, use, and retirement: product life cycle perspective

Overall results from the analysis through the life cycle lens are presented in Figure 13. The literature analyzed covers every phase through the product life cycle. Individual references consider - on average – about one and a half (1.52) life cycle phases. Apparently it is very difficult to construct modularity definitions that provide a good solution for all life cycle phases. The foregoing analysis that demonstrated how modularity optimized for one life cycle phase can differ considerably from modularity optimized for another phase, explains this finding.

The majority of the reference (42%) is directed to the production phase, slightly less than a third (29%) and a quarter (23%) to the use and design phases, respectively, and only a small share to the retirement phase (6%).

Figure 13 about here

Viewed separately, the engineering literature set exhibits a distribution across all life cycle phases that is different from the one of the management literature (Figure 14). As expected, the engineering oriented literature focuses mostly on the use phase. Designers think about what products are supposed to do for the user. The phase this literature focuses on with the second highest frequency is production. Manufacturing is another major engineering activity. In contrast, the management literature has its focus more on the design and production phases. This is partially caused by the operations management and operations research references that often have the processes of these two phases as their focus.

Figure 14 about here

6. Concluding Remarks

The analysis of the modularity literature through the 3 lenses allows a series of insights, both from each perspective individually and by taking the analysis as a whole.

First, the way in which modularity is described across the different publications varies with respect to both elements and relations, i.e., modules and interfaces. Both of these dimensions can show a variety of characteristics. Having multiple dimensions themselves, elements and relations are making modularity a nested, multi-dimensional construct. Modularity appears to be rather a bundle of product characteristics than a single condition.

Second, while function containment is, explicitly or implicitly, part of most modularity descriptions, what is understood as a function, however, can vary with when and where the modularization occurs. Market-driven modularity divides markets into segments and identifies product features that need to be separate and others that can be common. Here modules reflect product features from the market’s perspective. Modularization occurs during market research, i.e., *before* product design. In contrast, in case of technology-driven modularity the product is built by finding solutions for elementary technical problems, combining these technical solutions into subassemblies and modules, and ultimately into products. Modules are ‘formed’ by a combination and aggregation process of solutions to technical problems. Modularization occurs *during* product design. Depending on when modularity occurs, it exhibits very different attributes.

Third, the role, function, and relevance of both module and interface characteristics are interpreted differently depending on which life cycle phase is in focus. Designers favor low functional interactions to speed up the development process, producers promote easy installation of subassemblies, and users demand easy disconnection for maintenance purposes. Again, the resulting modularity for each life cycle phase differs from the next.

Taken as whole, the literature analysis presented allows to interpret the body of research on product modularity. In particular, the lack of operationalizability and the lack of a common language across disciplines become visible. Below I discuss each topic in detail, and suggest some directions for further research.

The underlying reason for why the question of how to operationalize modularity has often been avoided in the literature (with a few exceptions) is revealed in this review: it is very difficult to operationalize a concept that has been applied to so many different settings, and that, consequently, differs in so many dimensions, albeit sometimes only slightly. The idiosyncrasies of the few metrics that were developed in the literature stand testimony for this finding. Apparently, there is not a single definition for modularity that holds under all circumstances, and simultaneously is operationalizable. Nevertheless, I consider the question of how to operationalize modularity as extremely relevant. The lack of operationalizable measures of modularity makes it difficult to compare many of the existing studies. This literature analysis has presented observations, and provides some initial interpretations. As a next step causalities need to be investigated. What factors cause the differences in how modularity is interpreted and applied? What factors cause modularity occurrences at different points in time during the product creation process? What factors cause the choice of one life cycle stage over another when modularizing a product?

To address these questions, two directions seem worthwhile to be further pursued towards operationalizing modularity. Both directions acknowledge the multi-faceted character of module definitions along a product's life and across various participants' viewpoints. One direction represents the unpacking of the bundle modularity and the development of more precise measures on lower levels of complexity, which can be tied individually to points of modularity occurrence and life cycle phases.[18] The second direction approaches the question from the other end: to develop modularity assessments that integrate its complexity. For instance, by simultaneously considering multiple perspectives (see Tseng and Jiao, 1998, for an example of integrating structural, behavioral, and functional views) or multiple phases (e.g., product, production and sales in Du et al., 2000). Another option are nested approaches that sequence multiple goals (see Fujita and Yoshida (2001) for an example of optimization of module combination and module attributes for a family of aircrafts).

Together, the findings that each reference is on average concerned with only one and a half product life cycle stages and that modularity can occur at different points in the product creation process hints to the fact that there is no common language that is used and understood across the

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[18] While it has been suggested to introduce separate modularity descriptions for individual phases, i.e., modularity-in-design, modularity-in-production, and modularity-in-use (e.g., Baldwin and Clark, 2000, Sako and Murray, 1999), the analysis in section 5 shows that a operationalizable distinction probably would need to be much finer grained.

different areas working on the individual problems. An example for this problem is that despite the advantages that individual references present for individual modularity applications, there is very little known about the general nature of trade-offs across product life cycle stages or across disciplines. For example, as section 5 has shown, modularity is used in all stages of the product's life. The unanswered question, however, is: if modularity is applied in one stage, who gains and who looses in the other stages? The mechanics of the trade-offs involved are so far only poorly understood. To investigate these trade-offs a better handle on modularity is needed. This is second reason why it is crucial to find ways to operationalize modularity. Models and tools that help, for example, companies to assess the implications of product architecture choices on various stakeholder along a product's life are a promising research opportunity.

Just as individual life cycle stages are considered mostly in isolation, differences observed between market-driven and technology-driven perspectives show that there is too little understanding of the other side, respectively. What the modularity analysis demonstrates is that where and when the module creation occurs during the product creation process is important to grasp the meaning and intention of the selected module, and thus, both its role in the market and its technical constraints in the product and the product family. As such, this meaning is viewer specific. In other words, the translation process from customer perspectives in technical specifications is source for a number of variations in the modularity definition. Perhaps the detailed analysis presented in this paper can contribute to bridge this gap by providing a vocabulary of the various aspects and characteristics often associated with modularity.

Further research in this direction should also consider that this translation process is not only viewer specific but also dynamic in nature. Dynamic changes can be observed both on the market and the technology side of this translation process. In addition to the existing customer requirements, expectations for future replacements come into play. In other words, market segmentation is itself a dynamic process. Incorporating this effect will most likely require dynamic, multi-stage approaches (Allada and Lan (2002) present an example for new module launch planning). Not only the customer expectations change over time, but the modules themselves change. The underlying product and process technologies continuously develop, migrate, and converge, and this dynamic can have its own repercussions on the advantages and disadvantages of the individual modularity dimensions.

7. Appendix

Table 1: Modularity in the literature - engineering section (legend at the bottom of Table 2)

Reference		Systems Perspective		Hierarchy Perspective						Life Cycle Perspective				Industry / Product Example
	Author(s)/ Year	Description/ Variations of Elements	Description/ Variations of Relations	Tech. Modu-larity	Busin. Modu-larity	C	M	P	F	Des.	Prod.	Use	Retir.	
1	Allada and Lan, 2002	Parametric	Medium		X		X		X		X			*Model*
2	Allen and Carlson-Skalak, 1998	Configuration	Medium (count)	X			X	X				X	X	Video cassette
3	Chakravarty and Balakrishnan, 2001	Parametric	Low		X		X		X		X	(X)		*Model*
4	Cohen et al., 1992	Configuration	High	X			X	X				X		Industrial robot arm (SCARA type)
5	Coulter et al., 1998	Parametric	Medium (count)		X	X	X						X	Automotive center console
6	Dahmus et al., 2001	Fundamental	Low	X		X		X	X			X		Family of electric cordless drills
7	Dahmus and Otto, 2001	Fundamental	Low	X		X		X				X		Document handling system of a copy machine
8	Du et al., 2000	Parametric	Low	X		X		X			X	X		Office chair
9	Eppinger et al., 1994	Medium	Low		X	X		X		X				*Concept*
10	Erens and Verhulst, 1997	Fundamental	Medium	X	(X)		X	X	X	X	X			*Concept &* Cardiovascular system

Reference		**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Author(s)/ Year	Description/ Variations of Elements	Description/ Variations of Relations	Tech. Modu-larity	Busin. Modu-larity	C	M	P	F	Des.	Prod.	Use	Retir.	
11	Erixon et al., 1996	Configuration	High		X		X	X			X	X	X	*Concept only*
12	Fujita and Yoshida, 2001	Configuration	Low	(X)	X		X		X	X	X			*Model &* Aircraft family
13	Gonzalez-Zugasti and Otto, 2000	Configuration	Low	X			X		X		X			*Model &* Spacecraft family
14	Gonzalez-Zugasti et al., 2000	Configuration	Low		X	X		X	X			X		Space craft
15	Gu et al., 1997	Medium	Medium (count)	X		X	X	X				X	X	Vacuum cleaner
16	He and Kusiak, 1998	Parametric	Low		X		X	X			X			*Model for assembly process*
17	Hernandez et al., 2001	Parametric	Low		X		X		X		X	(X)		Absorption Chiller
18	Huang and Kusiak, 1998	Configuration	Medium (count)	X		X	X	X				X		Desk lamp & Electric motor
19	Ishii et al., 1995	Parametric	Low		X		X	X	X		X			Refrigerator door
20	Jiao and Tseng, 1999	Configuration	Low		X		X	X	X			X		Power supply units
21	Joneja and Lee, 1998	Parametric	Medium		X		X	X				X		Vibratory Bowl Feeder for Assembly processes
22	Kamrani and Salhieh, 2002	Fundamental	High	X	(X)	X	X	X		(X)	X	X		Four-Gear speed reducer

Reference		**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Author(s)/ Year	Description/ Variations of Elements	Description/ Variations of Relations	Tech. Modu-larity	Busin. Modu-larity	C	M	P	F	Des.	Prod.	Use	Retir.	
23	Kimura et al., 2001	Configuration	Medium	X		X	X					X	X	Car Air-Conditioner
24	Kohlhase and Birkhofer, 1996	Parametric	Low		X		X	X			X			Assembly Station
25	Kota and Sethuraman, 1998	Configuration	Low		X	X			X		X			Walkman
26	Kota et al., 2000	Configuration	Low		X	X			X	(X)	X			Walkman
27	Lin and Huang, 2000	Parametric	Low	X			X	X			X			Fixtures for Coordinate Measuring Machine
28	Marshall and Leaney, 2002	Fundamental	High	(X)	X		X	X			X	X		Test equipment for Drilling Applications
29	Martin and Ishii, 1996	Configuration	Low		X		X	X	X		X			Refrigerator door
30	Martin and Ishii, 2000	Configuration	High		X		X	X	X			X		Ink jet printer; thermoelectric water cooler
31	Martin and Ishii, 2002	Fundamental	High	X			X	X	X			X		Water Cooler
32	Mattson and Magleby, 2001	Fundamental	Medium		X		X		X	X	X	X		Power tool
33	McAdams et al., 1999	Fundamental	Low	X			X	X	X			X		Beverage brewers & material removal products
34	Nelson et al., 2001	Parametric	Low	X			X		X			X		Nail Gun

Reference		**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Author(s)/ Year	Description/ Variations of Elements	Description/ Variations of Relations	Tech. Modu-larity	Busin. Modu-larity	C	M	P	F	Des.	Prod.	Use	Retir.	
35	Newcomb et al., 1998	Configuration	Medium (count)		X		X	X					X	Automotive center console
36	Pahl and Beitz, 1996	Fundamental	Medium	X		X	X	X			X	X		Gearbox
37	Sand et al., 2001	Configuration	High	X		X	X					X	X	Two-way radio
38	Sharman et al., 2002	Configuration	High	X			X	X				X		Gas Turbine
39	Siddique and Rosen, 2000	Configuration	Medium (count)		X			X	X		X			Coffee maker
40	Siddique et al., 1998	Configuration	Medium (count)		X			X	X		X			Automotive underbody
41	Stone and Wood, 2000	Fundamental	Low	X			X	X				X		Hot air popcorn popper
42	Stone et al., 1998	Fundamental	Low	X		X	X	X				X		Electric screw driver
43	Stone et al., 2000a	Fundamental	Low	X			X	X				X		Lignite removal system & Electric wok
44	Stone et al., 2000b	Fundamental	Low	X			X	X	X			X		Electro-mechanical devices
45	Sudjianto and Otto, 2001	Fundamental	Low	X			X	X	X			X		Family of electric cordless drills
46	Tseng and Du, 1998	Configuration	Low	(X)	X			X	X		X	X		Power supply switch

Reference		**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Author(s)/ Year	Description/ Variations of Elements	Description/ Variations of Relations	Tech. Modu-larity	Busin. Modu-larity	C	M	P	F	Des.	Prod.	Use	Retir.	
47	Tseng and Jiao, 1996	Configuration	Low		X		X	X	X			X		Power supply for pulse width modulation
48	Tseng and Jiao, 1998	Configuration	Low		X		X	X	X		X	X		Power supply device
49	Ulrich and Eppinger, 2000	Fundamental	High	X		X	X	X	X		X	X		Motorcycle
50	Whitney, 1993	Configuration	Low		X	X		X	X	(X)	X			Automotive-panel meter; Radiator; Alternator
51	Wilhelm, 1997	Configuration	Low		X		X	X	X		X			Automobile
52	Yu et al., 1999	Parametric	Low		X		X		X			X		Toaster & Instant camera
53	Zhang et al., 2001	Configuration	Medium (count)	X		X	X						X	Flashlight

Table 2: Modularity in the literature - management section (legend at the bottom)

Reference		**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Author(s)/ Year	Description/ Variations of Elements	Description/ Variations of Relations	Techn. Modu-larity	Busin. Modu-larity	C	M	P	F	Des.	Prod.	Use	Retir.	
54	Ahmadi et al., 2001	Configuration	Medium		X		X	X		X				Rocket Turbopump
55	Baker et al., 1986	Parametric	Low		X	X		X			X			*Model*
56	Baldwin and Clark, 2000	Parametric	Medium		X		X	X		X				Computer
57	Browning, 2001	Configuration	High	X	(X)		X	X		X		X		Automobile Climate Control
58	Brusoni and Prencipe, 2001	Configuration	Low		X		X	X		X	X			Aero Engines & Chemical Plants
59	Chesbrough and Kusunoki, 1999	Parametric	Medium		X			X		X				Read-Write Heads for Disc Drives
60	Christensen et al., 2001	Parametric	Medium		X		X	X		X	X			Computers
61	Collier, 1982	Parametric	Low		X	X		X			X			*Model*
62	Desai et al., 2001	Parametric	Low		X	X		X	X		X			*Model*
63	Duray et al., 2000	Configuration	Medium		X		X	X		X	X			Cross-industry empirical study
64	Ernst and Kamrad, 2000	Parametric	Low		X	X		X	X		X			*Model*
65	Evans, 1963	Configuration	Low		X	X	X				X			*Model & Assortment example*

Reference		**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Author(s)/ Year	Description/ Variations of Elements	Description/ Variations of Relations	Techn. Modu-larity	Busin. Modu-larity	C	M	P	F	Des.	Prod.	Use	Retir.	
66	Feitzinger and Lee, 1997	Configuration	Low		X		X	X	X		X			Printer, PCs
67	Fisher et al., 1999	Parametric	Low		X	X		X	X		X			*Model* & Automotive Brakes
68	Galvin, 1999	Parametric	High		X		X			X				*Concept* & Bicycles
69	Garud and Kumaraswamy, 1995	Parametric	Medium		X		X	X		(X)	X			*Concept*
70	Garud and Kumaraswamy, 1996	Parametric	Medium		X		X			(X)	(X)	X	X	*Concept* & Object-Oriented Programming
71	Goldberg, 1991	Configuration	Low		X	X	X	X			X			*Model/ Heuristic*
72	Goldberg and Zhu, 1989	Configuration	Low		X	X	X	X			X			*Model &* Circuit Cards
73	Gulati and Eppinger, 1996	Fundamental	Low	X			X	X		X	(X)			Automotive Control Panel
74	Henderson and Clark, 1990	Parametric	Low		X		X	X		(X)		X		Photographic Alignment Equipment
75	Hwang and Rothblum, 1994	Parametric	Low	X		X	X				(X)	X		*Model*
76	Hyer and Wemmerlov, 1984	Parametric	Low	X		X	X			X	X			Elevator; Agricultural machinery

Reference		**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Author(s)/ Year	Description/ Variations of Elements	Description/ Variations of Relations	Techn. Modu-larity	Busin. Modu-larity	C	M	P	F	Des.	Prod.	Use	Retir.	
77	Karmarkar and Kubat, 1987	Configuration	Medium	X		X	X				X	X		*Model*
78	Kaski and Heikkila, 2002	Configuration	Medium	X			X	X			X			*Simulation* & Cellular Network Base Station
79	Kim and Chhajed, 2000	Parametric	Low	(X)	X		X		X		X			*Model*
80	Krishnan and Gupta, 2001	Parametric	Low	(X)	X	X		X	X	X				*Model* & Data Acquisition Equipment
81	Langlois and Robertson, 1992	Parametric	Medium		X		X	X		X	(X)	X		Hi-Fi Stereo equipment; Microcomputer
82	Lee and Tang, 1997	Configuration	Low		X		X	X			X			*Model &* Dishwasher
83	Loch et al., 2001	Configuration	High	X		X		X		X				*Model* & Door closing and locking mechanisms
84	MacDuffie et al., 1996	Configuration	Low		X	X		X	X		X			Automobile assembly
85	Meyer and Lehnerd, 1997	Configuration	Medium		X	X		X	X	X	X			Electric Iron
86	Muffatto, 1999	Configuration	Low		X		X	X		(X)	X			Automobile
87	Muffatto and Roveda, 2002	Fundamental	Explicit		X		X	X		X	X			*Concept*
88	O'Grady, 1999	Fundamental	Explicit		X	X	X	X		(X)	X			Computer Appliance

Reference		**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Author(s)/ Year	Description/ Variations of Elements	Description/ Variations of Relations	Techn. Modu-larity	Busin. Modu-larity	C	M	P	F	Des.	Prod.	Use	Retir.	
89	Pimmler and Eppinger, 1994	Fundamental	Explicit	X		X	X	X				X		Automotive climate control system
90	Pine, 1993	Parametric	Medium		X	X	X	X		(X)	(X)	X		Lighting controls
91	Randall and Ulrich, 2001	Parametric	Low		X	X		X			X			Bicycle
92	Robertson and Ulrich, 1998	Configuration	Medium		X	X	X		X	X	X	X		Automotive Instrument Panel
93	Sako and Murray, 1999	Configuration	Medium		X		X	X		X	X	X		Automobile
94	Salvador et al., 2002	Configuration	Medium		X		X	X	X		X			6 Cases: - small motorcycle, custom-phone, microwave, trucks, multiplexers, techoven
95	Sanchez, 2000	Parametric	Medium		X		X	X		X	X			*Concept*
96	Sanchez and Mahoney, 1996	Parametric	Medium		X		X	X		X	(X)	(X)		*Concept*
97	Schilling, 2000	Parametric	Medium		X		X	X		(X)	(X)	(X)		*Concept*
98	Shaftel, 1971	Configuration	Low		X	X	X				X			*Model & Assortment example*
99	Shaftel and Thompson, 1977	Configuration	Low		X	X	X				X			*Model & Assortment example*

Reference		**Systems Perspective**		**Hierarchy Perspective**						**Life Cycle Perspective**				**Industry / Product Example**
	Author(s)/ Year	Description/ Variations of Elements	Description/ Variations of Relations	Techn. Modu-larity	Busin. Modu-larity	C	M	P	F	Des.	Prod.	Use	Retir.	
100	Starr, 1965	Parametric	Medium		X		X	X	X	(X)	(X)			*Concept*
101	Thonemann and Brandeau, 2000	Parametric	Low		X	X		X	X		X			Automotive Wiring Harness
102	Tsai and Wang, 1999	Configuration	Explicit	X			X	X		X	X			Automated Guided Vehicle (AGV)
103	Ulrich, 1995	Fundamental	Explicit	X	(X)	X	X	X		(X)	X	X		*Concept;* Trailer
104	Veloso and Fixson, 2001	Parametric	Medium		X		X			(X)	X			Automotive Subsystems
105	von Hippel, 1990	Parametric	Low		X		X	X		X				*Concept*
106	Weng, 1999	Parametric	Low		X		X		X		X			Disposable Hospital Supplies
107	Worren et al., 2002	Parametric	Medium		X		X	X		X	(X)			Home Appliances

Legend for Table 1 and Table 2:

Systems Perspective:

Description/Variation of Elements/Modules: Parametric; Configuration; Fundamental

Description/Variation of Relations/Interfaces: Low, Medium, High

Hierarchy Perspective:

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

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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9. Figure and Tables

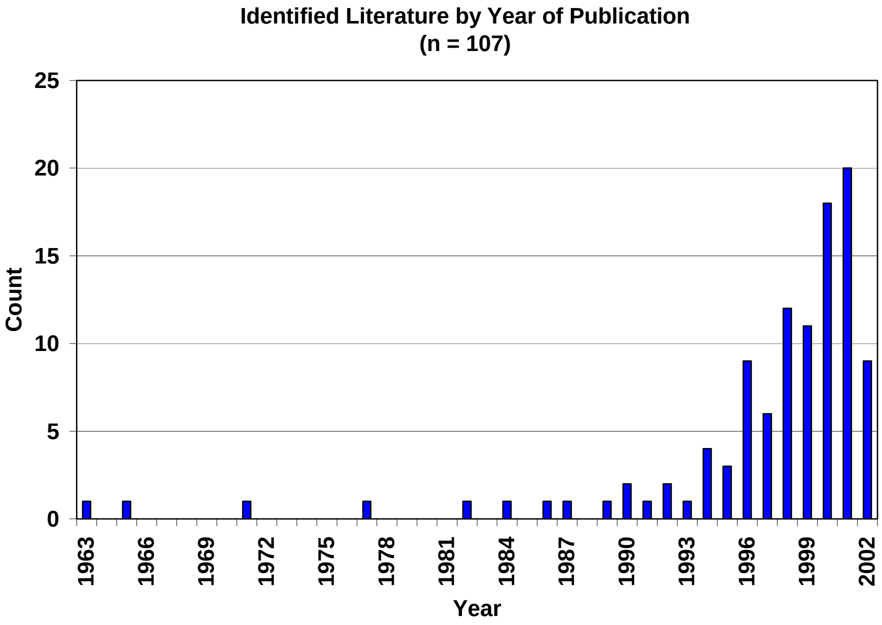

Figure 1: Identified literature

Table 3: List of Journals searched for this analysis

No.	Journal Title
1	Academy of Management Journal
2	Academy of Management Review
3	Administrative Science Quarterly
4	CIRP ANNALS-MANUFACTURING TECHNOLOGY
5	Computer in Industry
6	European Journal of Operational Research
7	Harvard Business Review
8	IEEE Transactions on Engineering Management
9	IEEE Transactions on Systems, Man, and Cybernetics A - Systems and Humans
10	IEEE Transactions on Systems, Man, and Cybernetics B - Cybernetics
11	IEEE Transactions on Systems, Man, and Cybernetics C - Applications and Reviews
12	IIE Transactions
13	Industrial and Corporate Change
14	International Journal of Advanced Manufacturing Technology
15	International Journal of Flexible Manufacturing Systems
16	International Journal of Production Economics
17	International Journal of Technology Management
18	Journal of Engineering and Technology Management
19	Journal of Engineering Design
20	Journal of Mechanical Design
21	Journal of Operations Management
22	Journal of Product Innovation Management
23	Management Science
24	Operations Research
25	Organization Science
26	Production and Operations Management
27	R&D Management
28	Research in Engineering Design
29	Research Policy
30	Robotics and Computer Integrated Manufacturing
31	Sloan Management Review
32	Strategic Management Journal
33	Technological Forecasting and Social Change
34	Technovation

Table 4: Source coding list (also used to separate the complete list into two; see Table 1 and Table 2)

	Engineering	Entries	Management	Entries
Journals	CIRP Annals	6	Academy of Management Review	1
	Computers in Industrial Engineering	1	Administrative Science Quarterly	1
	Computer in Industry	1	European Journal of Operational Research	7
	Design Studies	3	Harvard Business Review	4
	IEEE Transactions on Syst., Man, and Cybern. (A)	1	IEEE Transactions on Engineering Management	1
	IIE Transactions	3	Industrial and Corporate Change	1
	Journal in Engineering Design	2	International Journal of Production Economics	2
	Journal of Mechanical Design	7	International Journal of Technology Management	5
	Research in Engineering Design	5	Journal of Operations Management	2
			Management Science	9
			Operations Research	5
			Research Policy	3
			Sloan Management Review	1
			Strategic Management Journal	3
			Technological Forecasting and Social Change	1
Conference / Working Papers	ASME Design Engineering Technical Conferences	20	Working Papers, MIT Sloan School	2
			Working Paper, IMVP	1
Books / Book sections	Engineering Design (Pahl & Beitz)	1	Design Rules (Baldwin & Clark)	1
	Product Design & Development (Ulrich & Eppinger)	1	Power of Product Platforms (Meyer & Lehnerd)	1
	Product Design for Modularity (Kamrani & Salhieh)	1	The Age of Modularity (O'Grady)	1
	Section on Automotive Assembly (Wilhelm)	1	Mass Customization (Pine)	1
			Sect. on Modularity Trap (Chesbrough & Kusunoki)	1
TOTAL		53		54

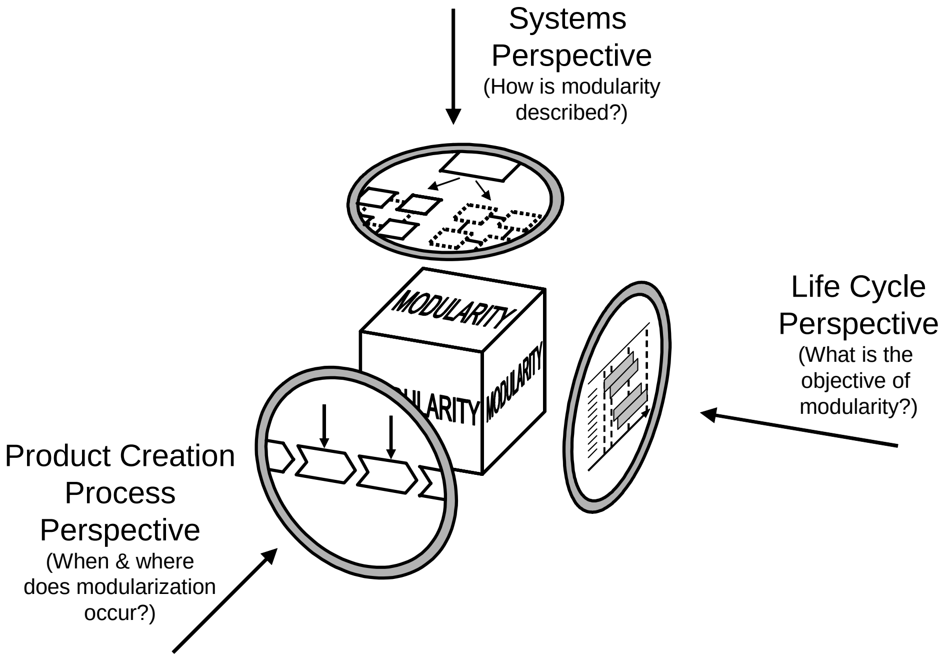

Figure 2: 3-Perspectives analysis framework

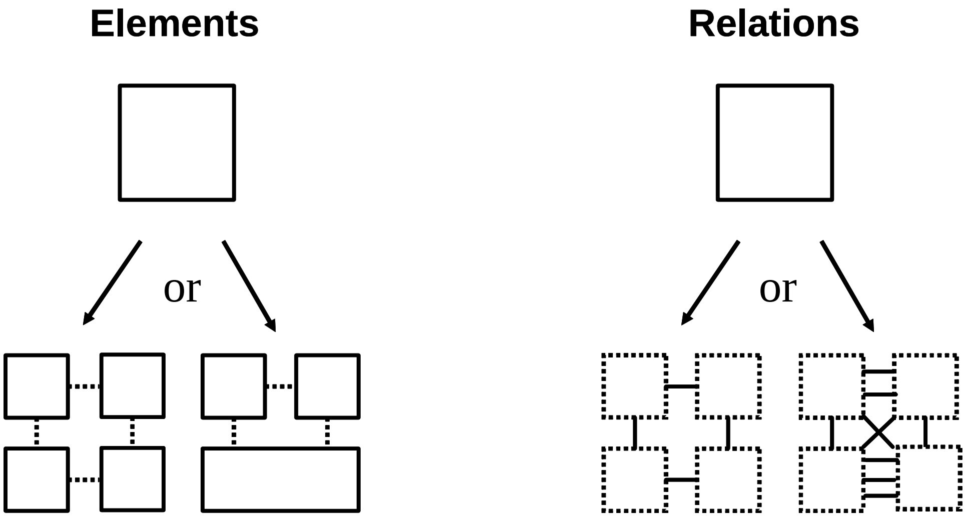

Figure 3: Two ways to describe modularity[19]

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[19] As an abstraction, assume that the two boxes in the top row represent two instances of a product. For each of the two instances, the bottom row suggests two ways of decomposing the products into smaller elements. Elements are represented by boxes and interfaces by lines. The difference between the two decompositions is that in one instance (left hand side) it affects only the elements (solid boxes) and assumes identical relations (dashed lines). Conversely, the decomposition in the second case neglects the elements (dashed) but focuses on the interfaces (solid) instead.

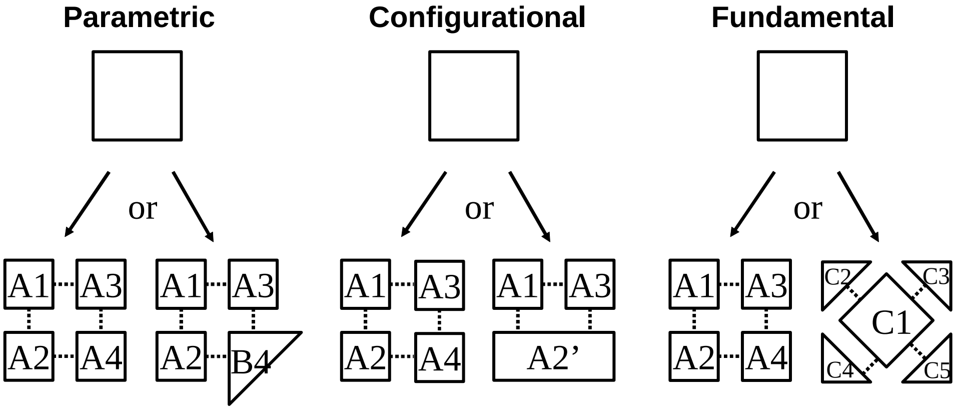

Figure 4: Three categories of element descriptions[20]

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[20] Again, assume that the area of the squares in the top row 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.).

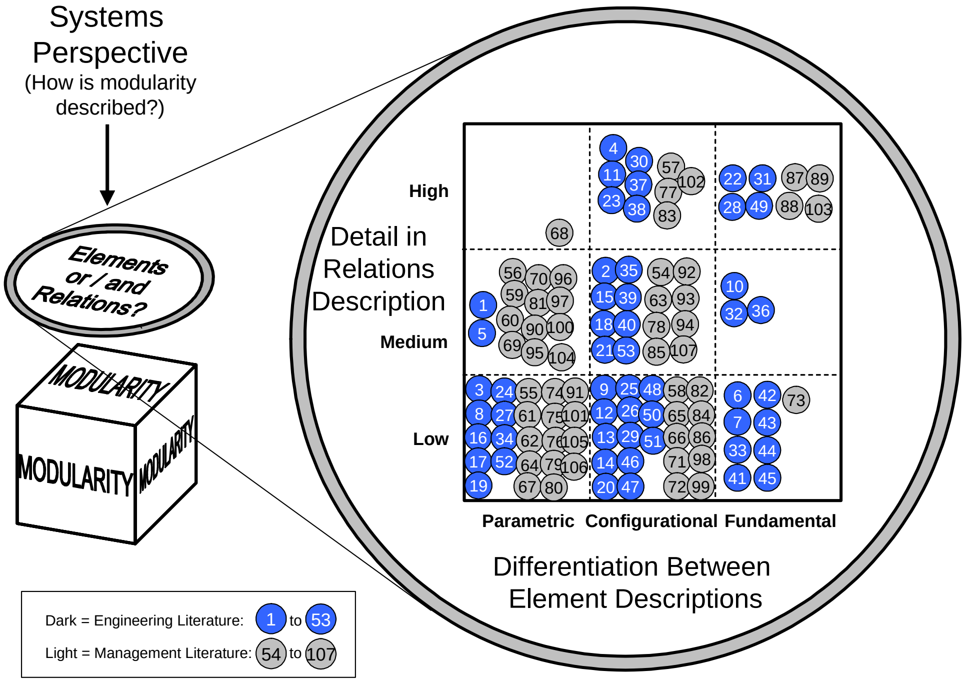

Figure 5: How modularity is described with elements and relations

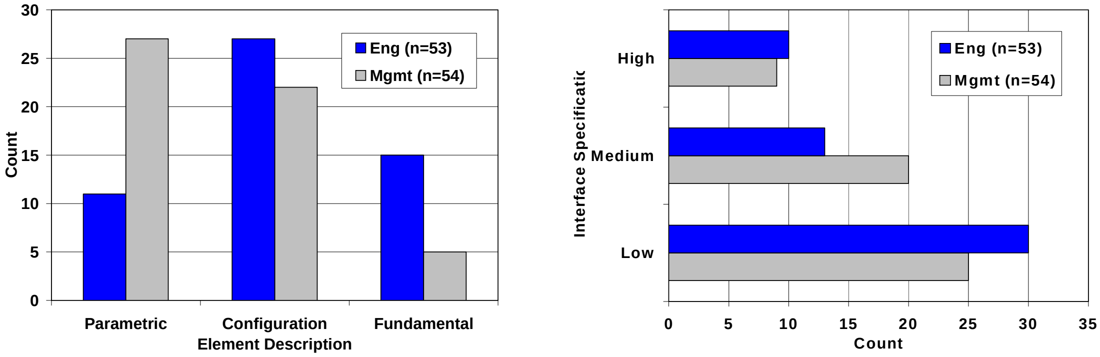

Figure 6: Engineering and management literature sets viewed from the systems perspective

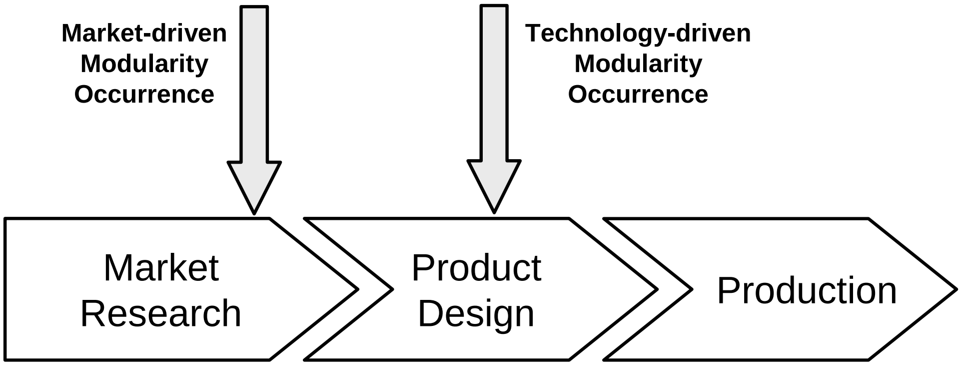

Figure 7: Product creation process

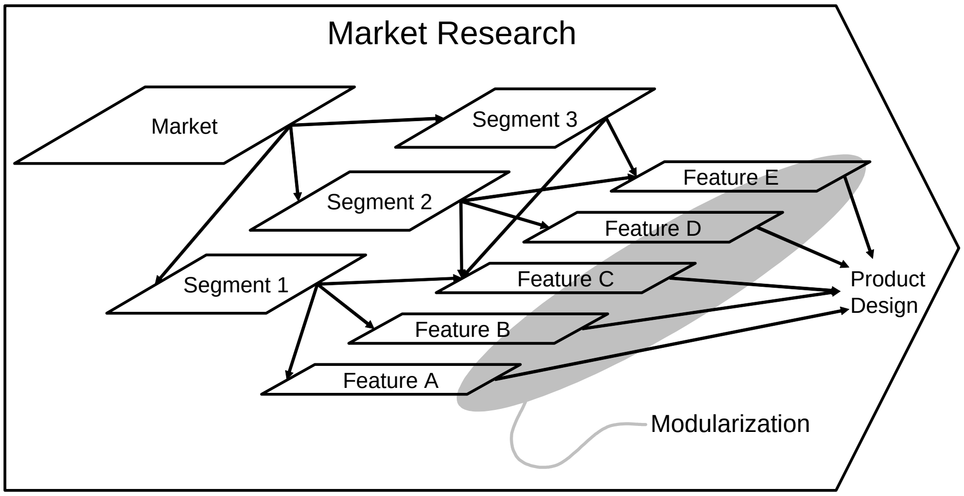

Figure 8: Modularity occurrence during market research

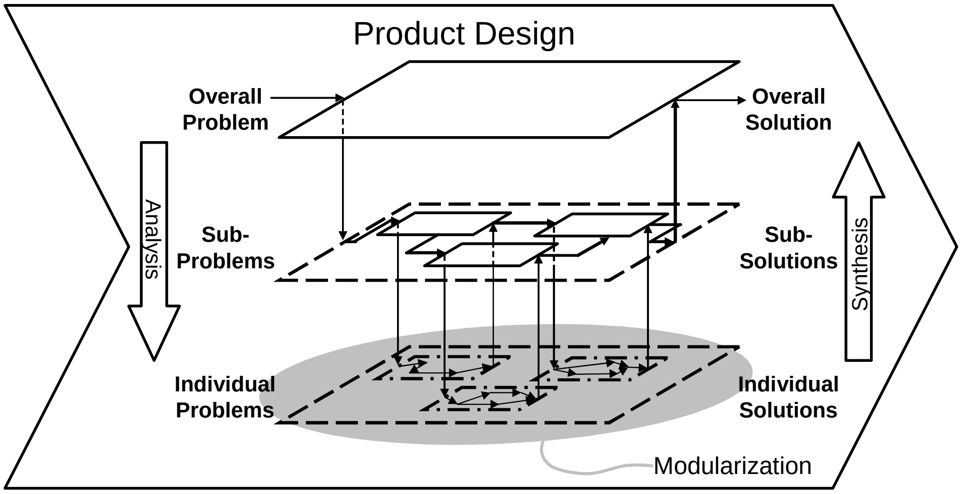

Figure 9: Modularity occurrence during product design (graphic adopted from Pahl and Beitz, 1996)

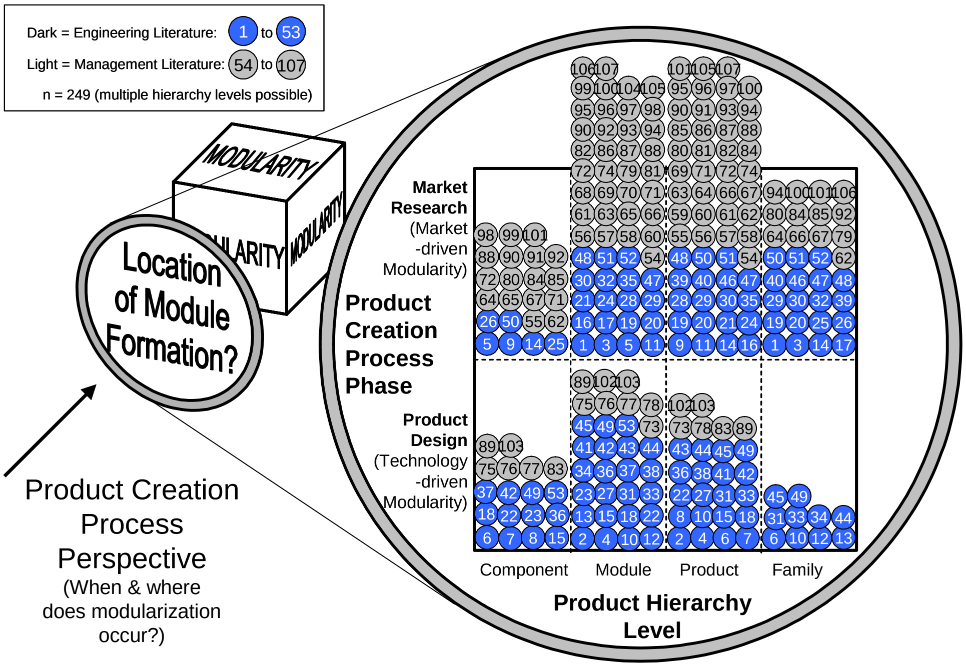

Figure 10: When (and where) modularity occurs during the product creation process

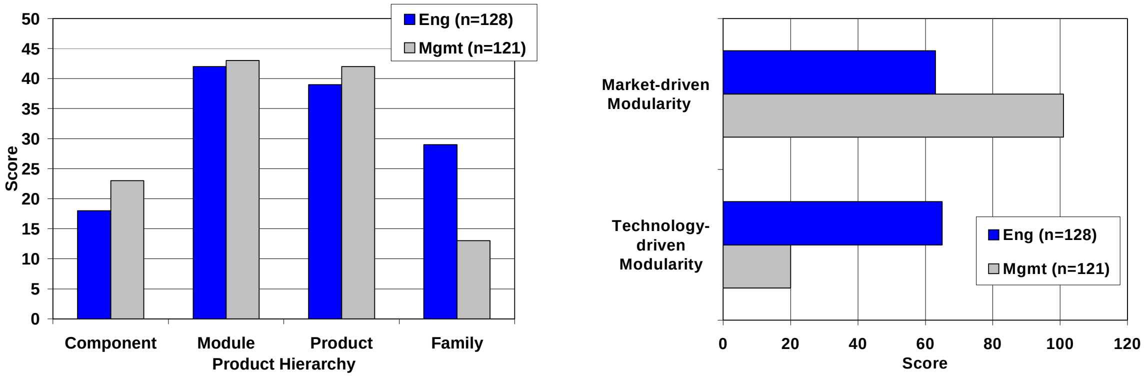

Figure 11: Engineering and management literature sets viewed from the process perspective

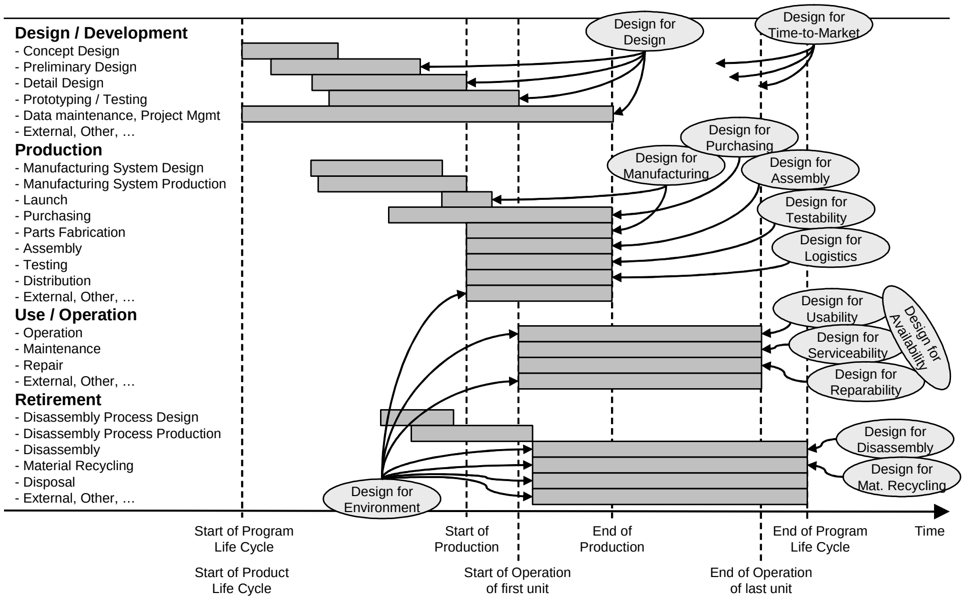

Figure 12: Product life-cycle phases

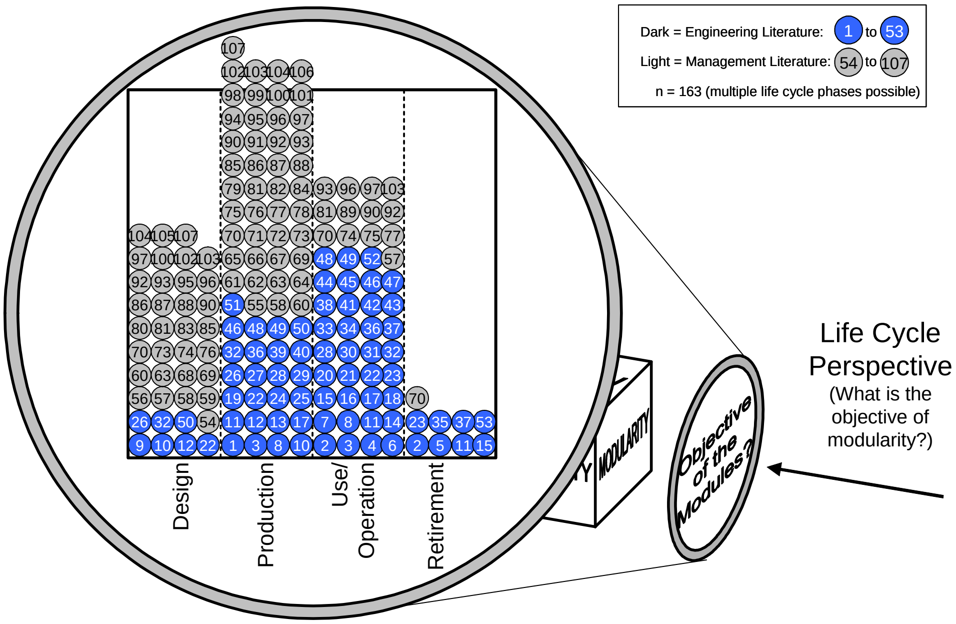

Figure 13: Focus on different life cycle phases when arguing for modularity

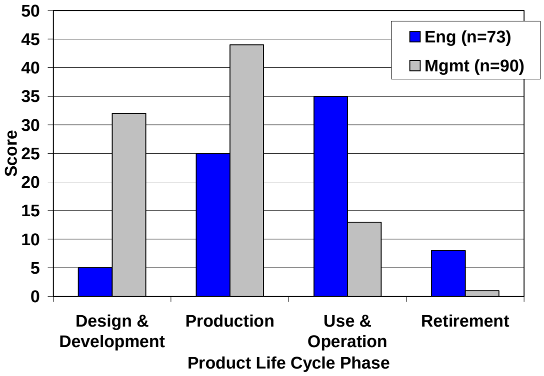

Figure 14: Engineering and management literature sets viewed from the life cycle perspective