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The answer depends on who you ask

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Abstract

‘Product modularity’ has recently experienced a significant increase in interest in the academic literature. While the concept of product modularity is used across a wide range of academic research areas, substantial variations exist in the ways in which the concept is described and interpreted. In this paper, I develop a framework to represent the similarities and differences that appear across these variations of the concept of product modularity. Next, through an extensive literature search I construct a set of 85 references representing the use of product modularity in the engineering and management literature over the past 30 years (1975–2006). With help of the framework I then analyze the use and interpretation of product modularity in every reference in the set. The analysis demonstrates that the product modularity concepts taken together really encompass a bundle of product characteristics rather than a single condition, and individual research areas exhibit certain preferences in which they define and operationalize product modularity. I conclude with some recommendations for future research. Overall, this paper strives to provide a vocabulary to improve cross-disciplinary understanding of product modularity.

Keywords

Product Modularity, Concept Ambiguity, Product Architecture, Interfaces, Multidisciplinary research, Review

1 Introduction

In recent years, product modularity has received increasing attention in both academia and industry. Scholars in various research communities across the engineering and management domains have identified many advantages of modular products. For instance, product modularity has been described as enabling faster product development through test cost reductions (Loch, Terwiesch, & Thomke, 2001) and allowing production of large product varieties at low cost (O'Grady, 1999). Product modularity is described as providing the customer with almost infinite opportunities to customize his product (Pine, 1993), and has been identified as harnessing unparalleled innovation rates (Baldwin & Clark, 2000). The increase in attention that product modularity received from academics is illustrated by the steep increase in publications on the topic over the past 15 years. Whereas until the early 1990s publications on product modularity occurred only sporadically, the number of annual publications has steadily increased since then, with an annual average of more than ten for the past five years (2002–2006).

Similarly, in industrial practice, examples of recent products that claim to be modular have spread beyond the ubiquitous example of the personal computer and range from small electronic devices to entire subsystems of the automobile. For example, Handspring designed its personal digital assistant (PDA) 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 (WARD's Auto World, 1999) or entire front-ends (Automotive Engineering International, 2001; Fourcade, Sandjvy, De Aquino, Ippolito, & Lima, 2003) are today delivered as modules to the assembly line.

The multitude of academic research efforts and industrial developments concerned with product modularity has produced many interesting results. However, this widespread interest has also produced a number of different ways of describing and defining product modularity, which are often similar, sometimes overlapping, yet often slightly different. For example, some sources focus on technical function containment as the characteristic feature of a module, 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 the representative feature of modularity. But then what exactly is product 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. First, the overlapping yet often slightly different descriptions and definitions of product modularity have made it difficult to empirically test product modularity's evolution, its causes, or its consequences. In fact, this lack of product modularity's operationalizability is likely to explain why there are very few empirical studies on product modularity (Fixson, 2007). Second, the gap between how product modularity is used in a conceptual way in some research areas, and how it is described in technical details in others, hinders potentially beneficial cooperation between these disciplines. For example, it is often difficult to translate conceptual or strategic findings on product modularity in one field into concrete product design advice in another.

It is not the purpose of this paper to add yet another definition of product modularity in the hope it will be the ultimate one. In contrast, the framework and the analysis in this paper strive to unpack and compare the existing concepts of product modularity to make their similarities and differences visible. The analysis results help explain how the different definitions and viewpoints relate to each other, and it illustrates that modularity really is a bundle of product characteristics rather than a one-dimensional condition, and different views emphasize different elements of this bundle. These insights are expected to facilitate empirical work and cross-disciplinary collaboration on product modularity.

Two boundaries limit the scope of this paper. The first boundary is set by the subject of the analysis. It is concerned with modularity concepts and ideas for industrially manufactured products. The second boundary defines the literature considered for this paper. Although it has been found that the concept of modularity has been 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.[1]

The remainder of the paper is structured as follows. In the next section I develop a two-dimensional framework to analyze and compare the different descriptions of product modularity. Section three presents in detail the selection process for the set of literature references. Section four shows how all references can be represented in one of three categories in each of the two dimensions *modules* and *interfaces*. It also illustrates how different domains and research areas place their emphases on different aspect of the modularity bundle. Section five concludes with some recommendations on future research directions.

2 A Framework to Compare Product Modularity Concepts

Trying to capture how product modularity is described and defined by scholars from various disciplines quickly leads to the concepts of modules and the dependencies between them. An often encountered notion of modularity describes modules as exhibiting relatively weak interdependencies between each other and relatively strong interdependencies within them (Alexander, 1964; Ulrich, 1995; Baldwin & Clark, 2000; Schilling, 2000).

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[1] With the focus of this paper on industrially manufactured hardware products, the literature selected for this paper excludes sources that are explicitly non-hardware related such as computer science and software engineering journals. As a consequence, the vast majority of the articles is concerned with hardware products, with only a few software related-references (see section 3 for details).

However, operationalizing this conceptually powerful measure has proven quite challenging. For example, what role do modules play in determining modularity? Is a product with many small modules more modular than a product with few but large modules, or vice versa? Similarly, if the level of interdependence of a subunit with other subunits is a pre-condition for the subunit to represent 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?

To develop a framework to compare the various approaches that define and operationalize product modularity, I borrow from the systems engineering literature where a system is determined by its elements and the relations between them (Maier & Rechtin, 2000). Adapting this view, two dimensions for product modularity descriptions can be defined: (i) the elements the product consists of, i.e., its modules, and (ii) the relations, i.e., the interfaces, between these elements. Figure 1 illustrates the difference between these two dimensions. 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 connecting the boxes. The difference between these two archetypes of decompositions is that in one instance (left hand side) the decomposition affects only the elements (solid boxes) and assumes identical relations between (dashed lines), whereas the decomposition in the second case neglects the elements (dashed) but focuses on the differences of the interfaces (solid) instead.

Insert Figure 1 about here

2.1 Modules: a product's elements

To specify what a module is requires the decomposition of a product. This process can follow various logics to arrange the product structure. For example, one can attempt 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). Other structuring rationales may be component lifetimes, innovation rates, materials, or cost.

For the framework developed here I cluster the existing approaches in three categories of module description. The categories differ from each other by the extent to which they consider how functions are allocated to the product's elements. In the simplest case which I term 'parametric,' the elements' functional boundaries are fixed and only predetermined elements can be exchanged. The second case, labeled 'configuration,' allows to group smaller elements into larger ones to form modules. Finally, the 'fundamental' case permits a complete re-allocation of functions to the elements. Figure 2 illustrates the differences between the three categories. 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, i.e., modules.

Insert Figure 2 about here

2.2 Interfaces: the relations between the product’s elements

The extent to which the relations between a product’s elements, i.e., its interfaces, have been described in the literature varies significantly, both in qualitative and quantitative terms. For the framework developed here I distinguish three categories by their levels of description detail. The first category exhibits the lowest level of detail in its interface descriptions of the three. It typically assumes that whatever the role of the interface for the product function is, it is not impacted by the choice of modules and components. For example, the literature on inventory savings through common components often makes the implicit assumption of identical interfaces. In other words, the first category does not consider interface specifications in any detail.

The second category shows a medium level of detail regarding the description of interfaces. It encompasses two sub-types of interfaces descriptions. The first sub-type indicates the required interchangeability with a general notion of ‘standardization.’ In fact, in some cases interface standardization has been touted as the determining factor for product modularity. The second sub-type uses simple interface counts for modularity specifications. For example, several ratios have been developed that use interface counts as a way to measure modularity.

The third category adds qualitative assessments to the interface description. This assessment of the quality can occur in two ways. One way is simply to indicate the ‘strength’ of an individual interface. This strength measure distinguishes different levels of dependence of the components participating in the interface under consideration. Another way of qualitatively distinguishing interfaces is to detail their physical nature. For example, an interface could transmit mechanical forces, electrical current, material, or information.

3 Reference Set Construction

To construct the data set for the analysis in this paper I followed a four-step procedure. First, I developed an extensive list of relevant academic journals. This list of journals encompasses 36 English-language journals, half from the engineering domain, half from the management domain (see Table 1).[2] While this list does cannot claim to be exhaustive, it does exhibit substantial overlap with other papers that have studied the relevance of various journals in the engineering management and technology innovation literature. For example, my list includes eleven of the top twelve journals identified as the most relevant journals in technology innovation management by Cheng and Co-authors (1999), and it includes eight of the top ten identified by Linton and Thongpapanl (2004) for the same field. Overall, the set of journals covers a wide range of topics such as design, manufacturing, operations, management, organization, and strategy. The net was cast purposefully wide to ensure a comprehensive coverage of the literature because product modularity has been discussed in a number of research areas.

In a second step, I conducted a search in all 36 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 over 30 years of publications (1975–2006)[3] but the majority of references identified was published after 1990. As search term I used ‘modularity.’ The ISI Web of Science system searches for a search term in title, keywords, and abstract of all articles. The initial search resulted in 121 hits.

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[2] In Table 1 I list the journals in two categories, one for engineering journals, the other for management journals. While for some journals an association to either category could have been justified, particularly for the operations journals, for most of the journals the assignment to one of the categories is rather straightforward.

[3] The three in the ISI Web of Science database included indices cover 34 years (Science Citation Index Expanded: 1973-present), 34 years (Social Sciences Citation Index (SSCI): 1973-present), and 32 years (Arts & Humanities Citation Index (A&HCI): 1975-present) of publications.

The third step constituted the removal of all references from the list that were caught by the initial search procedure but that did not addressed modularity in a product-related context. For example, papers were removed that found modularity purely in processes, algorithms, organizations, or abstractly in innovations. Similarly, if modularity was only peripherally mentioned, e.g., in the editor-added keyword list, but did not play any meaningful role in the article itself, I removed the reference from the list. I also excluded all references from the list that directly reviewed other individual works, e.g., book reviews, or were communications between researchers, e.g., comments and responses to comments. In total, I removed 48 references.

In a fourth step I added twelve references to the list. In five cases these were references that were widely cited in the community working on the topic of modularity (but not caught in the initial search because they did not contain the search term in title, abstract, or keyword list).[4] The remaining seven references are books. These books are either widely known text books for product development and product design classes (Pahl & Beitz, 1996; Ulrich & Eppinger, 2000; Kamrani & Salhieh, 2002), or they are books that have established important ideas in which modularity plays a central role, for example mass customization (Pine, 1993), product platforms (Meyer & Lehnerd, 1997), or modularity itself (Baldwin & Clark, 2000). The final list contains 85 references. Table 1 provides the details of the data set construction process.

Insert Table 1 about here

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[4] An example is the 1990 ASQ article by Henderson and Clark on Architectural Innovation that had been cited 681 times as of March 2007 but was not caught by the original search.

4 Product Modularity Concepts in the Literature

To unpack the dimensions along which product modularity usages differ (or overlap), and the extent to which they do so, I first apply the framework introduced above to the list of references and determine each reference's location in the framework. I structure the discussion along the clusters that the framework creates. In a second and third step I analyze the existing product modularity descriptions on more aggregated levels. Although the search covered a timeframe of over 30 years, since most of the references were published post 1990, the data base overall is too small to detect change processes longitudinally. Thus, all following analyses study the data cross-sectionally.

4.1 Applying the framework to the reference set

4.1.1 Module descriptions using the parametric approach

The parametric approach considers the product structure as essentially fixed, and allows the variation of product characteristics only within the boundaries of individual elements. In other words, only one (or a few) design parameter(s) are changed, i.e., parameterized, while all others remain constant. This approach can be stylized by the substitution of one sub-unit through another one which exhibits different characteristics (see the replacement of A4 with B4 in Figure 2). Real-life examples for this approach are color changes of face-plates at cell phones; or the use of different power sources in otherwise identical products, e.g., power tools.

In the literature the parametric approach is prevalent in studies that discuss the advantages of product modularity – and some of its disadvantages – on a conceptual level. Examples are works with a focus on the variety-permitting effects of modularity's mix-and-match capability in the factory (Starr, 1965; Watanabe & Ane, 2004), in the supply chain (Salvador, Rungtusanatham, & Forza, 2004), or for the customer (Langlois & Robertson, 1992). Similarly, references focusing on the cost saving effect through the commonality-related aspect of modularity via the retention and reuse of components often follow a parametric approach when describing modules (Garud & Kumaraswamy, 1996; Kim & Chhajed, 2000). Also, references that have their focus more on higher-level consequences of modularity such as innovation diffusion (Galvin, 1999), productivity increases (Majumdar, 1997), organizational learning (Sanchez, 2000), supplier selection (Hoetker, 2006), or industry evolution (Lei, 2000) tend to view modules from a parametric perspective. Finally, references that measure modularity with approximations such as the patent ownership by suppliers vs. the one of assemblers of PCs (Kodama, 2004), the ratio of initial component cost to integration cost (Anderson & Parker, 2002), or the degree to which respondents agreed to the statement that "products have been decomposed into separate modules" (Worren, Moore, & Cardona, 2002:1131) fall in the parametric category. In summary, 24 of the 85 references take on a parametric approach when describing modules.

4.1.2 Module descriptions using the configuration approach

The second category of decomposition approaches assumes the smallest building blocks as fixed, and produces the product architecture by arranging these components into larger units (A2+A4 or A2', configuration case in Figure 2). For instance, for a vacuum cleaner, should the motor and the fan jointly form one module or two separate ones? This approach presupposes existing, basic elements, and the architecture definition concentrates on the determination of how these elementary elements are grouped into larger ones, i.e., the modules.

What many of the works in this category attempt to do is to determine the appropriate level of hierarchy at which to establish modules, i.e., the number and size of the modules. The criteria that are used for this process vary. Some researchers have investigated the effect of hierarchy level at which modules are designed on innovation and adaptation performance (Ethiraj & Levinthal, 2004b), others have looked at performance of product development processes via parallelizing activities (Tsai & Wang, 1999) or via alignment of the architectures of product and developing organization (Sosa, Eppinger, & Rowles, 2003, 2004), both affected by the modularity configuration. Other criteria that have been used to identify good or optimal module configurations include the maximization of module use across members of a product family (Kota, Sethuraman, & Miller, 2000; Du, Jiao, & Tseng, 2001; Kusiak, 2002; Zhang, Tor, & Britton, 2006), the optimal degree of desired customization (Jiao & Tseng, 1999; Hofer & Halman, 2004; Kumar, 2004), the minimization of maintenance cost (Tsai, Wang, & Lo, 2003), the minimization of supply chain cost (Huang, Zhang, & Liang, 2005), the minimization of associated communication efforts in service businesses (Verganti & Buganza, 2005), and the best environmental performance at the product's end-of-life (Newcomb, Bras, & Rosen, 1998). A major tool developed to help in this module formation process are design structure matrices (Steward, 1981) and its various derivatives (Browning, 2001). Some of these matrices indicate the components' level of suitability to belong to one and the same module along multiple criteria (Huang & Kusiak, 1998; Jose & Tollenaere, 2005) or simple similarity assessments (Kamrani & Gonzalez, 2003). Fundamentally, the configuration problem has been around for a while. In the earliest article in the analyzed set of references Evans (1963) introduced over forty years ago the problem of optimizing assortments under the name 'modular design.' He developed an algorithm that found the optimal allocation of individual components to component kits for multiple purposes.

Empirical works that measure modularity indirectly through questions such as whether 'options can be added to a standard product' or whether 'new product features are designed around a standard base unit' also fit into the configuration category (Duray, Ward, Milligan, & Berry, 2000; Duray, 2004).

Finally, some researchers have explored whether system complexity can actually prevent the initial (and secondary) identification of useful (and optimal) module configurations. For example, Ethiraj and Levinthal (2004a) extent the interpretation of their simulation results – originally derived for organizational structures – to product structures and suggest that the existence of hierarchy enables to find good, workable modules through relatively local search processes. It has been found that in situations after an external environmental shock to treat these decisions dynamically is particularly beneficial (Siggelkow & Levinthal, 2003). As for the ability for a firm to sustain competitive advantage Pil and Cohen (2006) propose that modularity in product design is detrimental because it invites faster imitation by competitors but simultaneously is beneficial in that it helps the focal firm to explore the solution space better.

The underlying assumption of the configuration approach 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 total, 46 of the 85 references fall in the configuration category with respect to the module description.

4.1.3 Module descriptions using the fundamental approach

While the configuration approach is constrained by the pre-definition of sub-module level components, the fundamental 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 2). 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’). A similar re-allocation of relative importance of individual functions while maintaining existing components – a fundamental approach in our setting – has been termed architectural innovation (Henderson & Clark, 1990).

The fundamental approach is followed by references that reflect modularity by the way functions are mapped to components (Ulrich, 1995; Fixson, 2005). Several sources suggest ways to operationalize the concept of allocating product functions to components. For example, one way to find new function-component allocations is to map the functions onto potential modules and then assess the viability of these potential modules along various criteria (O'Grady, 1999). While this method might create a new allocation scheme, it does so within the constraints of existing components. To overcome this problem requires higher levels of abstraction, i.e., a focus on what the functions of a product actually are. For example, Cetin and Saitou find the optimal level of modularity of spot-welded structures by concentrating on structural performance (Cetin & Saitou, 2004b, 2004a). Similarly, the method of mapping functional requirements into design parameters is typical for this approach (Salhieh & Kamrani, 1999; Bi & Zhang, 2001). More generally, methods to establish abstract functions structures to describe modular (and non-modular) product structures are proposed by several textbooks in the product and engineering design field (Pahl & Beitz, 1996; Ulrich & Eppinger, 2000; Kamrani & Salhieh, 2002).

Compared to the configuration category, approaches in the fundamental category employ a higher level of abstraction (physical functions instead of basic components) to determine modularity. Only 15 out of 85 references follow the fundamental approach to describe modules.

4.1.4 Interface descriptions with low level of detail

The dimension ‘interface’ can also be distinguished in three different categories. The category that exhibits a low level of detail in its interface description is represented by references 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. In other words, while for example part commonality is stressed as an important aspect in supply chains, the ensuing implications for the interface specifications are often silently assumed. This effect can be observed in situations in which the focus is on modeling the effects of parts commonality on firm profitability (Kim & Chhajed, 2000), or in which the concentration is on platform effects on innovation performance (Lei, 2003) and competitive advantage (Jones, 2003). Similarly, some of the more abstract design work that focuses on the matching procedure between functional requirement and physical representation falls into this category. For example, Moon and Kota (2002) present a method to map required machining operations on a set of preconfigured machining modules, and Cetin and Saitou (2005) model the trade-off between manufacturing costs and structural strength for different structures. In total, 21 of the 85 references fall into the first interface category characterized by low levels of detail in interface descriptions.

4.1.5 Interface descriptions with medium level of detail

The category that shows a medium level of detail regarding the description of interfaces 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 determining factor for product modularity: “Production of components conforming to standard interface specifications also leads to modularity.” (Garud & Kumaraswamy, 1995:94) 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 & Mahoney, 1996:66). The notion that standardized interfaces allow mixing and matching of components to create product variety appears in studies of products as diverse as aerospace products (O'Sullivan, 2003), computers (Baldwin & Clark, 1997, 2000), elevators (Mikkola & Gassmann, 2003), lighting controls (Pine, 1993), power tools (Meyer & Lehnerd, 1997), software (Blackburn, Hoedemaker, & Van Wassenhove, 1996; Nambisan, 2002; Baldwin & Clark, 2006; MacCormack, Rusnak, & Baldwin, 2006), telecommunications equipment (Kaski & Heikkila, 2002; Staudenmayer, Tripsas, & Tucci, 2005), textbooks (Schilling, 2000), windshield wipers (Mikkola, 2003), online broker services (Buganza & Verganti, 2006), and woodworking machines (Germani & Mandorli, 2004). The term combinatorial modularity has been introduced to describe the same phenomenon (Salvador, Forza, & Rungtusanatham, 2002; Fine, Golany, & Naseraldin, 2005), and concepts such as build-to-order (BTO) (Mukhopadhyay & Setoputro, 2005) and product platforms (Muffatto & Roveda, 2000; Simpson, 2004) are often based on the same assumption.

The second subgroup consists of references that advocate the use of interface counts for modularity specifications. For example, Zhang and Gershenson (2003) count component-component interactions within and across modules to construct a measure of modularity. Also using an interface count, Mikkola and Gassmann estimate the degree of coupling as the ratio of the number of interfaces per component in a subsystem of a given product architecture (Mikkola & Gassmann, 2003; Mikkola, 2006). In total, slightly more than half of the references (45 of 85) fall in the category of medium-level detailed interface descriptions.

4.1.6 Interface descriptions with high level of detail

There are two ways in which an article can exhibit a high level of detail in interface description. The first sub-cluster incorporates a qualitative assessment of the interfaces, i.e., a measure of some interface ‘intensity.’ To approximate this interface intensity measures have been suggested that count the mappings between functional and physical elements (Loch et al., 2001), that (subjectively) assess the redesign effort complexity in case a function that flows through the interface is changed (Holtta & Otto, 2005), that recognize a component’s performance as a function of the performance of neighboring components (Loch, Mihm, & Huchzermeier, 2003), or that assess the impact of design change propagation through the product (Veenstra, Halman, & Voordijk, 2006).

The second possibility in which a source can demonstrate a high level of detail in its interface description is by detailing 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 interface (Gershenson, Prasad, & Zhang, 2003, 2004). In sum, 19 of 85 references fall in the category of interface descriptions with high-level of detail. Table 2 summarizes the analysis of all 85 references in the two-dimensional framework.

Insert Table 2 about here

4.2 Comparing product modularity concepts across academic domains

As the previous section illustrates, the engineering and management literature streams contain product modularity concepts that differ in the underlying assumptions on product decomposition as well as on the level of detail in which interface characteristics are included. Given that the extant literature as a whole fills all categories along the two dimensions *modules* and *interfaces*, it is worthwhile to explore whether membership to academic domain or research area leads to clusters along these dimensions. Both domain and research areas association are established at the source level, i.e., the journal, not the individual article.

The 36 journals searched for the analysis presented in this paper have been associated with either the domain *engineering* or the domain *management* (first column in Table 1). Consequently, the set of selected references can be split along those lines in two subsets, encompassing 35 references in engineering, and 50 references in management. Both domains show similar growth rates in publication numbers over the past 15 years (Figure 3).

Insert Figure 3 about here

The distributions of these two subsets along the two dimensions *modules* and *interfaces* vary substantially (top portion of Table 3). For modules, whereas 60% of the engineering references fall into the configuration category and only 11% can be found in the parametric category, of the management references 50% and 40%, respectively, fall in these categories. Conversely, only 10% of the management references are found in the category of fundamental approaches to module descriptions whereas almost a third of the engineering references are represented in this category. Clearly, the engineering literature exhibits a substantially greater presence in the category that requires more technical details for the module description.

With respect to interface descriptions, the references of the engineering set split across the three levels of details evenly with about a third in each category. In contrast, about two thirds of the management references appear in the medium level category – primarily due to the fact that this category includes the label ‘standardization’ – and about one sixth in each the low and the high level of detail categories. On the surface, standardization appears to be a term most people would agree on what it means – at least conceptually. This is why the term is so prevalent in works that discuss product modularity, and interfaces in particularly, on a rather conceptual level.

Insert Table 3 about here

4.3 Comparing product modularity concepts across six research areas

To further explore the potentially different perspectives held by research areas that differ in their focus, research model, and publication outlets, I assigned each journal to one of the following six research areas: engineering design, manufacturing engineering, operations research/management science/industrial engineering, operations management, engineering management, and general management (third column in Table 1).[5] In turn, each reference in the set is associated with one of these six research areas. The textbooks added to the list are associated with either engineering design or general management. The resulting distributions for each research area along the two dimensions modules and interfaces are presented in the bottom portion of Table 3. All research areas show similar distributions over time (Figure 4), thus the analyses below view the data set cross-sectionally.

Insert Figure 4 about here

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[5] Note that the research areas operations research/management science/industrial engineering and operations management do not exactly align with the domains engineering and management.

With respect to the differences in module description, the engineering management and the general management research areas clearly emphasize the parametric approach with 53% and 50%, respectively. Second in both research areas is the configuration approach with 47% and 35%, and the fundamental approach is pursued only by a small fraction of the general management research area. In contrast, all of the remaining four research areas favor the configuration approach; between 55% (engineering design) and 90% (OR/MS/IE) of their respective references fall in this category. The two operations areas have only a few references in either the parametric or the fundamental approach category. Only the engineering design research area (and to a lesser extent the manufacturing engineering research area) has a significant presence in the fundamental approach category of module description. This result is not surprising as these two areas have at their core the design and manufacturing of products, both activities that require detailed decisions about the product architecture.

The distributions for the six research areas along the dimension level-of-detail in interface description follow mostly similar patterns. As indicated above, the notion of interface standardization plays an important role in most of the management literature. Consequently, about two thirds of the references of both the engineering management and the general management categories fall in the medium-level of detail in interface description category with the remaining third evenly distributed on the low and high level categories. The reference set of the operations management area exhibits the same distribution, albeit with an even smaller dispersion. The set of references of the design engineering research area is again the only one with a substantial presence in the category with high level of detail in interface description (measured in percent that is also true for OR/MS/IE but the small sample size cautions any interpretation). In fact, almost half of all references that use high-level of detail in their interface description (19) belong to the design engineering research area (9).

5 Concluding Remarks

The analysis of the set of references with help of the framework introduced in this paper demonstrates that there exist a variety of definitions and descriptions of product modularity, and they are not all identical, albeit often overlapping. These descriptions differ in the relative emphasis they put on the description of the two dimensions *modules* and *interfaces*, and they differ regarding the use of some underlying assumptions within each dimension. In the dimension of module description, some assume the underlying product architecture as fixed and allow only the simple replacement of components, others assume a product architecture allowing combinatorial variations (but no divisions), and yet other permit the complete re-allocation of functions to components. In the dimension of interface description, the approaches vary on the level of detail they provide. Some neglect this aspect of product modularity entirely, some simply state the existence of standardized interfaces, and others describe in detail physical nature and intensity of individual interfaces.

The fact that the set of literature references analyzed for this paper covers the entire spectrum of descriptions as mapped by the framework shows both the breadth and variety of product modularity concepts in academic work, and the difficulty of cross-disciplinary work originating from this breadth and variety. One way to overcome this difficulty in communication between research areas is to unpack the concept of product modularity into more elementary product features that afford more precise construct descriptions and definitions. Alternatively, the development of descriptions of product modularity that are portable across research areas and simultaneously allow operationalization for empirical testing would be a promising field for future research. For either endeavor the framework laid out in this paper can provide the vocabulary to foster empirical and cross-disciplinary work of product modularity, its causes, and its consequences.

One limitation of this work lies in its data cut-off in 2006. Although the search process covered more than 30 years (1975–2006), significant data is only available for the past 15 years, and even within the past decade and a half the recent strong growth trend in publication numbers makes longitudinal analyses very difficult because the data in the early period is too limited. Nevertheless, past experience shows that concepts postulated and defined at some point in time can shift over time. An example of this effect is illustrated by the study of the use and migration of Brooks' ideas on project management as published in his book *The Mythical Man-Month* (Brooks, 1995 (1975)) across different subject areas (McCain & Salvucci, 2006). Similar temporary shifts in interpretation are entirely possible for the concept of product modularity, and a longitudinal study of its evolution presents another fruitful future research avenue.

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7 Tables and Figures

No.	Journal Title	Research Area[1]	References identified in initial search	References removed due to focus on: Process[2]	Algorithm[3]	Organiz.[4]	Innovation[5]	Periph.[6]	Comm.[7]	References added	References included in final analysis
Engineering Journals											
1	Artificial Intelligence for Engineering Design Analysis and Manufacturing	ED	3								3
2	CIRP ANNALS - Manufacturing Technology	MFG	0								0
3	Concurrent Engineering - Research and Applications	ED	5	1	1						3
4	Design Studies	ED	1								1
5	European Journal of Operational Research	OR/MS/IE	2								2
6	IEEE Transactions on Systems, Man, and Cybernetics A - Systems and Humans	OR/MS/IE	1								1
7	IEEE Transactions on Systems, Man, and Cybernetics B - Cybernetics	OR/MS/IE	2		2						0
8	IEEE Transactions on Systems, Man, and Cybernetics C - Applications and Reviews	OR/MS/IE	0								0
9	IIE Transactions	OR/MS/IE	3		2			1			0
10	International Journal of Advanced Manufacturing Technology	MFG	7		5						2
11	International Journal of Flexible Manufacturing Systems	MFG	2					1			1
12	Journal of Engineering Design	ED	4								4
13	Journal of Intelligent Manufacturing	MFG	6		3						3
14	Journal of Mechanical Design	ED	8		1						7
15	Operations Research	OR/MS/IE	0							1	1
16	Production Planning & Control	OM	5	1	1			1			2
17	Research in Engineering Design	ED	1								1
18	Robotics and Computer Integrated Manufacturing	MFG	3		2						1
Engineering Books		ED								3	3
Total Engineering References			*53*	*2*	*17*	*0*	*0*	*3*	*0*	*4*	*35*
Management Journals											
19	Academy of Management Journal	GM	1			1					0
20	Academy of Management Review	GM	3						1		2
21	Administrative Science Quarterly	GM	1							1	2
22	Harvard Business Review	GM	3				1		1	1	2
23	IEEE Transactions on Engineering Management	EM	3								3
24	International Journal of Technology Management	EM	8	1				1			6
25	Journal of Engineering and Technology Management	EM	1								1
26	Journal of Operations Management	OM	7					1			6
27	Journal of Product Innovation Management	EM	5						1		4
28	Management Science	OR/MS/IE	8				1	1			6
29	Organization Science	GM	7	1		5					1
30	Production and Operations Management	OM	2					1			1
31	R&D Management	EM	1								1
32	Research Policy	GM	5	1			3	1		2	2
33	Sloan Management Review	GM	1						1		0
34	Strategic Management Journal	GM	8			2		1			5
35	Technological Forecasting and Social Change	EM	2								2
36	Technovation	GM	2								2
Management Books		GM								4	4
Total Management References			*68*	*3*	*0*	*8*	*5*	*6*	*4*	*8*	*50*
GRAND TOTAL			**121**	**5**	**17**	**8**	**5**	**9**	**4**	**12**	**85**

[1] ED: engineering design; MFG: manufacturing; OR/MS/IE: operations research/management science/industrial engineering; EM: engineering management; GM: general management; OM: operations management
[2] References focus on modularity of processes or services
[3] References focus on modularity of algorithms, modeling approcheas, or scheduling architectures
[4] References focus on modularity of innovations in the abstract
[5] References focus on modularity of organizations
[6] References refer to modularity only peripherally
[7] References are commentaries on other reference(s) in the initial list (e.g., book review), or reponse letters.

Table 1: Reference selection process

Detail of Interface Description	**High**	Galvin 1999; Loch et al. 2003; Sanchez 2000	Browning 2001; Gershenson et al. 2003, 2004; Loch et al. 2001; Sosa et al. 2003, 2004; Tsai and Wang 1999; Veenstra et al. 2006	Fixson 2005; Hollta and Otto 2005; Kamrani and Salhieh 2002; O'Grady 1999; Pahl and Beitz 1996; Salhieh and Kamrani 1999; Ulrich 1995; Ulrich and Eppinger 2000
	Medium	Anderson and Parker 2002; Garud and Kumaraswamy 1995, 1996; Hoetger 2006; Langlois and Robertson 1992; Majumdar 1997; Mikkola 2003; Pine 1993; Salvador et al. 2004; Sanchez and Mahoney 1996; Schilling 2000; Starr 1965; Staudenmayer et al. 2005; Worren et al. 2002	Baldwin and Clark 1997, 2000, 2006; Blackburn et al. 1996; Buganza and Verganti 2006; Du et al. 2001; Duray 2004; Duray et al. 2000; Hofer and Halman 2004; Huang and Kusiak 1998; Jose and Toolenaere 2005; Kamrani and Gonzalez 2003; Kaski and Heikkila 2002; MacCormack et al. 2006; Meyer and Lehnerd 1997; Mikkola 2006; Mikkola and Grassmann 2003; Muffatto and Roveda 2000; Mukhopadhyay and Setoputro 2005; Nambisan 2002; Newcomb et al. 1998; O'Sullivan 2003; Pil and Cohen 2006; Salvador et al. 2002; Siggelkow and Levinthal 2003; Simpson 2004; Verganti and Buganza 2005; Zhang and Gershenson 2003	Bi and Zhang 2001; Fine et a;. 2005; Germani and Mandorliu 2004
	Low	Jones 2003; Kim and Chhajed 2000; Kodama 2004; Lei 2000, 2003; Moon and Kota 2002; Watanabe and Ane 2004	Ethiraj and Levinthal 2004a, 2004b; Evans 1963; Huang et al. 2005; Jiao and Tseng 1999; Kota et al. 2000; Kumar 2004; Kusiak 2002; Tsai et al. 2003; Zhang et al. 2006	Cetin and Saitou 2004a,b, 2005; Henderson and Clark 1990
		Parametric	**Configuration**	**Fundamental**
		Category of Module Description		

Table 2: Reference set in analysis framework

	Approach to Module Description								Level of Detail in Interface Description							
Domain	**Parametric**		**Configuration**		**Fundamental**		**TOTAL**		**Low**		**Medium**		**High**		**TOTAL**	
Engineering	**4**	11%	**21**	60%	**10**	29%	**35**	100%	**12**	34%	**12**	34%	**11**	31%	**35**	100%
Management	**20**	40%	**25**	50%	**5**	10%	**50**	100%	**9**	18%	**33**	66%	**8**	16%	**50**	100%
Sum	**24**		**46**		**15**		**85**		**21**		**45**		**19**		**85**	

	Approach to Module Description								Level of Detail in Interface Description							
Research Area	**Parametric**		**Configuration**		**Fundamental**		**TOTAL**		**Low**		**Medium**		**High**		**TOTAL**	
Engineering Design	**2**	9%	**12**	55%	**8**	36%	**22**	100%	**7**	32%	**6**	27%	**9**	41%	**22**	100%
Manufacturing Engineering	**0**	0%	**5**	71%	**2**	29%	**7**	100%	**3**	43%	**3**	43%	**1**	14%	**7**	100%
Oper. Res./ Mgmt Science / Ind. Eng.	**1**	10%	**9**	90%	**0**	0%	**10**	100%	**3**	30%	**4**	40%	**3**	30%	**10**	100%
Operations Management	**2**	22%	**5**	56%	**2**	22%	**9**	100%	**1**	11%	**7**	78%	**1**	11%	**9**	100%
Engineering Management	**9**	53%	**8**	47%	**0**	0%	**17**	100%	**3**	18%	**11**	65%	**3**	18%	**17**	100%
General Management	**10**	50%	**7**	35%	**3**	15%	**20**	100%	**4**	20%	**14**	70%	**2**	10%	**20**	100%
Sum	**24**		**46**		**15**		**85**		**21**		**45**		**19**		**85**	

Table 3: Distributions of references for modules and interfaces by domain and research area

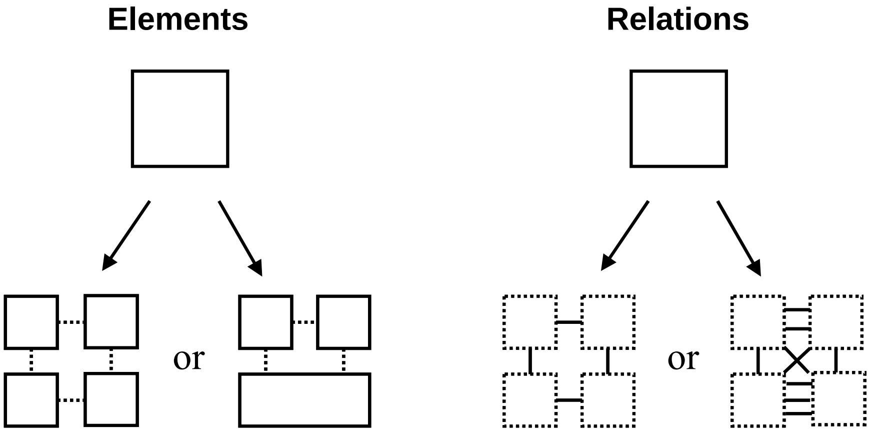

Figure 1: A Systems Engineering Perspective on Product Modularity

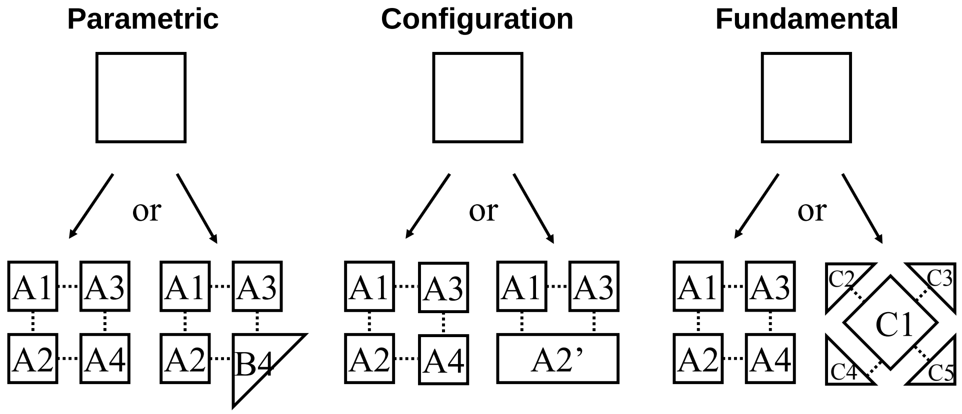

Figure 2: Three Categories of Element Descriptions

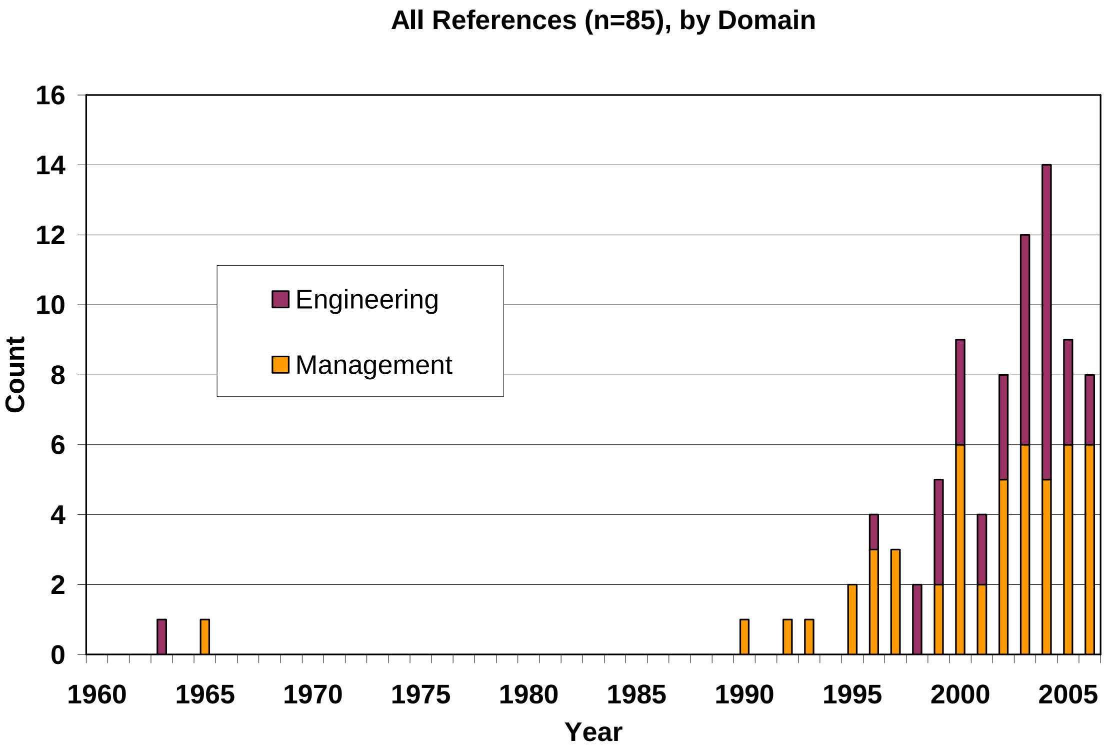

Figure 3: All references by publication year (1960 – 2006) and domain

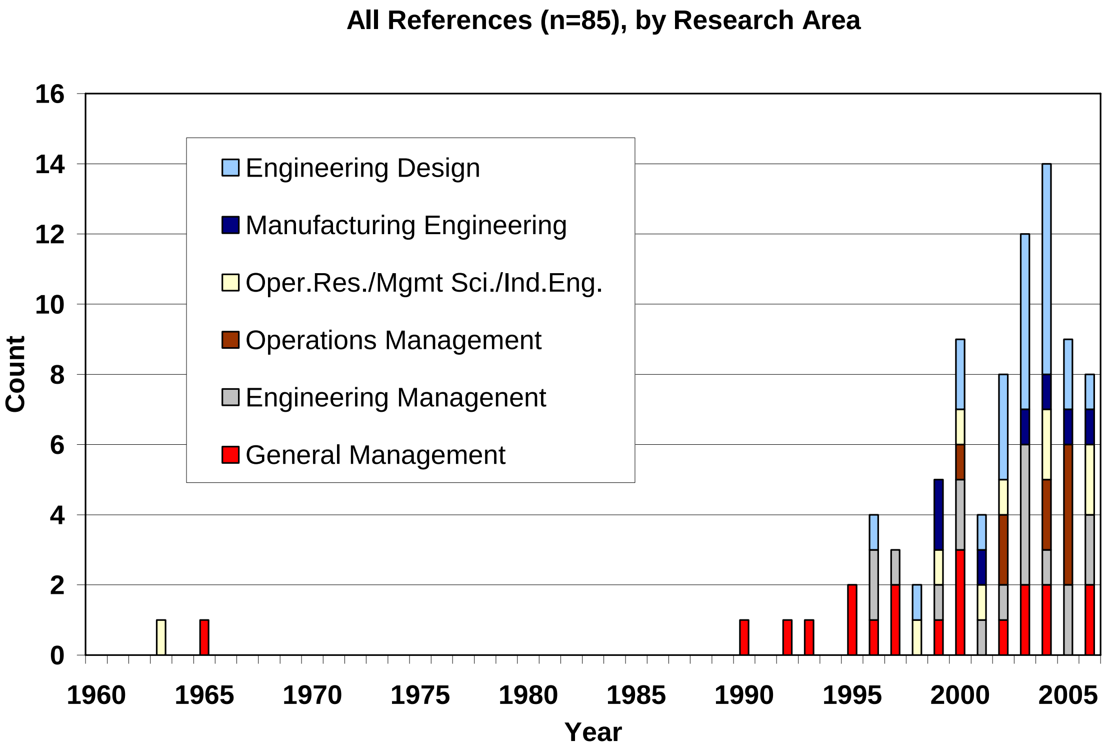

Figure 4: All references by publication year (1960 – 2006) and research area