PRODUCT ARCHITECTURE MODULARITY STRATEGIES:

TOWARD A GENERAL THEORY

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ABSTRACT

The focus of this paper is to integrate various perspectives on product architecture modularity into a general framework, and also to propose a way to measure the degree of modularization embedded in product architectures. Various trade-offs between modular and integral product architectures and how components and interfaces influence the degree of modularization are considered. In order to gain a better understanding of product architecture modularity as a strategy, a theoretical framework and propositions are drawn from various academic literature sources. Based on the literature review, the following key elements of product architecture are identified: components (standard and new-to-the-firm), interfaces (standardization and specification), degree of coupling, and substitutability. A mathematical function, termed modularization function, is introduced to measure the degree of modularization embedded in product architectures, by taking the key elements as the main variables. Various managerial and theoretical implications of the modularization function are drawn. For instance, the function can be used as a framework to aid to examine various leveraging forces behind new product development, manufacturing, and supply chain management policies of a firm. The modularization function also allows us to study the implications of modularization from different theoretical perspectives, such as resource-based view of the firm and transaction cost economics. Finally, the application of the modularization function and its limitations are discussed.

Key words: modularity, product architecture

INTRODUCTION

In broadest terms, modularization is an approach for organizing complex products and processes efficiently (Baldwin & Clark, 1997), by decomposing complex tasks into simpler portions so they can be managed independently and yet operate together as a whole. Through standardization of interfaces, modularization permits components to be produced separately, or 'loosely coupled' (Orton & Weick, 1990; Sanchez & Mahoney, 1996), and used interchangeably in different configurations without compromising system integrity (Flamm, 1988; Garud & Kumaraswamy, 1993, 1995; Garud & Kotha, 1994). From a system's perspective, modularization can be described as a continuum outlining the degree to which a system's components can be decomposed and recombined. It refers both to the tightness of coupling between components and the degree to which the "rules" of the system architecture enable (or prohibit) the mixing-and-matching of components (Schilling, 2000). Decomposition of a complex system into smaller, more manageable parts has been well covered in management literature [e.g., scientific management principles with respect to standardized work designs and specialization of labor (Taylor, 1967), sociology literature [e.g., nearly decomposable systems[1] (Simon, 1962)] as well as in economics literature (e.g., Adam Smith's view on division of labor and task partitioning). One of the earlier pieces of literature describing modularization as a strategy was the 'modular production concept' (Starr, 1965), which described the essence of modular production concept to design, develop, and produce parts which can be combined in

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[1] According to Simon (1962:129), "(a) in a nearly decomposable system, the short-run behavior of each of the component subsystems is approximately independent of the short-run behavior of the other components; (b) in the long-run, the behavior of any one of the components depends in only an aggregative way on the behavior of the other subcomponents."

maximum number of ways in order to deal with consumers' demand for variety and uniqueness. Accordingly, throughout the 1960s and 1970s, many optimization models were introduced, mostly focusing around manufacturing issues related to modularization (cf. Rutenberg, 1971; Rutenberg & Shaftel, 1971; Charnes & Kirby, 1965; Evans, 1963; Dogramaci, 1979), such as the 'modularity problem'[2].

There are many reasons why firms pursue modularization as a new product development (NPD) strategy. For one, modular product designs enable firms to increase specialization (Langlois, 2000), encouraging them to pursue specialized learning curves and increasing their differentiation from competitors (Schilling, 2000) as well as benefiting from decreased throughput times with elimination of pre-assembly operations (Wilhem, 1997). Modularity may also boost the rate of innovation, and as long as the design rules are followed, more experimentation and flexibility are given to designers to develop and test the modules (Baldwin & Clark, 1997). Other advantages of modularization include cost reduction (Muffatto, 1999), economies of scale and scope (Pine, 1993; Friedland, 1994), increased flexibility (Schilling, 2000; Sanderson & Uzumeri, 1997; Sanchez & Mahoney, 1996), and increased competition among suppliers (Langlois, 1992; Langlois & Robertson, 1992; Tassey, 2000; Baldwin & Clark, 1997). Modular products may protect a firm's market power and architectural control, especially when it has control of some unique assets, or has accessibility to complementary assets (Teece, 1986). However, to protect such assets from competitors (such as through reverse engineering or pirating) can be

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[2] The 'modularity problem' refers to an optimal design problem, in which only one variant of assembly is built, but different applications and quantities of this assembly are used to create more variants (Dogramaci, 1979; Emmons & Tedesco, 1971; Evans, 1963; Passy, 1970; Shaftel, 1971; Smeers, 1974).

challenging. The extent of control and accessibility to complementary assets determine, to some degree, whether a firm leans towards an integral or a modular solution to product architecture designs. There is performance, time, and cost trade-offs associated with modular and integral product architecture designs. Modular systems are much harder to design than comparable interconnected systems because the designers of modular systems must know a great deal about the overall product or process in order to develop the visible design rules necessary to make the modules function as a whole (Baldwin & Clark, 1997). This means that interface designs with respect to integration of parts must be done carefully in terms of defining and organizing the modules. Rigidity can be introduced by modularization if cost benefits were exploited and flexibility must be maintained on model changes, as this does not encourage standardization through module development (Muffatto, 1999).

Modularization strategies are closely associated with product architecture choices in terms of the constituent components and how these components are linked with each other. The literature on modularization mentions various aspects on product architecture design and management such as trade-offs between modular and integral product architectures (cf. Ulrich & Eppinger, 1995; Schilling, 2000; Robertson & Ulrich, 1998; Ulrich, 1995; Chesbrough & Kusunoki, 2001; Meyer & Lehnerd, 1997; Meyer & Utterback, 1993; Meyer, Tertzakian & Utterback, 1997; Sanderson & Uzumeri, 1997; Fine, 1998), cost and performance implications (cf. Baldwin & Clark, 1997; Muffatto, 1999; Pine, 1993; Langlois & Robertson, 1992; Henderson & Clark, 1990; Christensens & Rosenbloom, 1995), economies of scale and scope (Pine, 1993; Friedland, 1994), standardization of interfaces (Ulrich, 1995; Tassey, 2000; Link & Tassey, 1987; Sanchez, 1999), substitutability (Garud & Kumaraswamy, 1993, 1995), synergistic specificity (Schilling, 2000; Schilling & Steensma, 2001), and mixing-

and-matching (cf. Sanchez & Mahoney, 1996; Sanchez, 1999; Garud & Kumaraswamy, 1995; Schilling, 2000). The effects of modularization as a NPD strategy not only impact industry standard settings in the value chain but also the long-term technology strategy and policy of the firm with respect to architectural innovations and modular innovations[3].

The focus of this article is to integrate various perspectives on product architecture modularity into a general framework, and also to propose a way to measure the degree of modularization embedded in product architectures. Specifically I focus on the trade-offs between modular and integral product architectures and how components and interfaces influence the degree of modularization. In order to gain a better understanding of product architecture as a NPD strategy, a theoretical framework and propositions are drawn from various academic literature sources. Based on the literature review, key elements of product architecture are identified: components (standard and new-to-the-firm), interfaces (standardization and specification), degree of coupling, and substitutability. Each proposition indicates one element that influence the degree of modularization embedded in product architectures. A mathematical model termed 'modularization function' is introduced as a tool to

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[3] Architectural innovations are (Henderson & Clark, 1990:10) "innovations that change the way in which the components of a product are linked together, while leaving the core design concepts untouched." The emphasis of an architectural innovation, often triggered by a change in a component, is the reconfiguration of an established system to link together existing components in a new way. Modular innovations, on the other hand, are innovations that change only the relationships between core design concepts of a technology without changing the product's architecture. It is the introduction of new component technology inserted within essentially unchanged product architecture (Christensen & Rosenbloom, 1995).

systematically evaluate the combined effects of the key elements as well as their managerial and theoretical implications.

The paper is organized as follows. Trade-offs between modular and integral product architecture designs are discussed next, followed by the literature review identifying the key elements of product architectures. Then a general model of product architecture modularity is presented along with testable propositions. Next, the modularization function is introduced as a way to operationalize the combined effects of the key elements on the degree of modularization. Finally managerial and theoretical implications of the research model and limitations of the modularization function are presented.

PRODUCT ARCHITECTURES

Product architecture can be described as the arrangement of the functional elements of a product into several physical building blocks, including the mapping from functional elements to physical components, and the specification of the interfaces among interacting physical components (Ulrich & Eppinger, 1995). Its purpose is to define the basic physical building blocks of the product in terms of both what they do and what their interfaces are with the rest of the device. Product architectures can range from integral to modular. In integral product architectures, one-to-one mapping between functional elements and physical components of a product is non-existent, and interfaces shared between the components are coupled (Ulrich, 1995), or highly interdependent. Changes to one component cannot be made without making changes to other components. Integral architectures are designed with maximum performance as a goal, hence enhancing knowledge sharing and interactive learning as team members rely on each other's expertise in designing the architecture. With integral

product architectures, firms may be able to customize their products to satisfy each customer's particular needs. Costs of customized components tends to be higher due to the integral nature of product architectures where an improvement in functional performance can not be achieved without making changes to other components. As the interfaces of the customized components become standardized, costs are significantly reduced as changes to product architecture can be localized and made without incurring costly changes to other components.

Contrary to integral product architectures, modular product architectures are used as flexible platforms for leveraging a large number of product variations[4] (Gilmore & Pine, 1997; Meyer et al., 1997; Robertson & Ulrich, 1998; Sanchez & Mahoney, 1996), enabling a firm to gain cost savings through economies of scale from component commonality, inventory, logistics, as well as to introduce technologically improved products more rapidly. Some of the motivations for product change include upgrade, add-ons, adaptation, wear, consumption, flexibility in use, and reuse (Ulrich & Eppinger, 1995). Product variants often are achieved through modular product architectures where changes in one component do not lead to changes in other components, and physical changes can be more easily varied without adding tremendous complexity to the manufacturing system. Outsourcing decisions are often made concurrently with the design of modular product architectures, and specialization of knowledge is gained through division of labor. For example, unlike the quasi-integral architecture of Apollo Computer, Sun Microsystems relied on a simplified, non-proprietary architecture built mainly with off-the-shelf hardware and software, including the widely available UNIX system. Only two proprietary modules

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[4] Ulrich & Eppinger (1995) defined variety as the range of product models the firm can produce within a particular time period in response to market demand.

were developed in-house to link the microprocessor efficiently to the workstation's internal memory. However, only using two proprietary components was not enough to lock Sun's customers into its own proprietary operating system or network protocols as they were easily copied and could not be patented (Baldwin & Clark, 1997). This raises the following questions: Is there an optimum number of proprietary components in a given product architecture? What are the fundamental trade-offs between integral and modular product architecture designs with respect to proprietary component composition?

KEY ELEMENTS OF PRODUCT ARCHITECTURE MODULARITY

In devising a modular product architecture strategy, there should be a balance between the gains achievable through recombination (e.g., mixing-and-matching) of components and the gains achievable through specificity (e.g., higher performance through components) in determining the pressure for or against the decomposition of a system (Schilling, 2000). Although modular designs increase flexibility in the product by allowing a variety of possible configurations to be assembled (Garud & Kumaraswamy, 1995; Baldwin & Clark, 1997), it also increases the coordination effort of these components. Too much product variety for customers to choose from may actually create frustration and can backfire, especially when customers are not able to distinguish the performance, quality, and value among different components. Nissan, for instance, retreated from customization when it became evident that buyers did not want eighty-seven different varieties of steering wheels (Pine, Victor & Boynton, 1993). Another example is Volkswagen. One of the uncertainties faced by Volkswagen is on order volume and mix, and product variety only adds to the obsolescence risks. Consequently, the strategy of limiting variety (such as through platform sharing) is actively pursued in the supply chain. Although large volumes are

considered favorable for efficiency, they aggravate the long cycle times and poor service. This is reflected on Volkswagen Passat's delivery time to a consumer to about 12 months (van Hoek, 2001). Product architecture strategies consider many tradeoffs, such as design criteria, architecture redesign, nature of components, nature of innovation, to name a few. Some contrasting characteristics of modular and integral product architectures are summarized in Table 1.

Table 1. Characteristics of Modular and Integral Product Architectures.

	Modular Product Architecture	Integral Product Architecture
Design criteria	Commonality sharing	Maximum performance
Component boundaries	Easy identification	Difficult identification
Redesign to architecture	Without modification	With modification
Interfaces	Decoupled	Coupled
Outcome	Economies of scale	Craftsmanship
Product variants	High	Low
Nature of components	Standardized/generic	Customized/dedicated
Component outsourcing	Easy	Difficult
Learning	Localized/Dispersed	Interactive
Synergistic specificity	Low	High
Component substitutability	High	Low
Component recombinability	High	Low
Component separability	High	Low
Nature of innovation	Autonomous	Systemic
System design strategy	Decomposition	Integration

Product configurations are rooted in product architecture designs, be integral or modular, and the degree of modularization inherent in product architectures is sensitive and dependent upon the constituent components and respective interfaces in relation to the system as a whole. Issues regarding to decomposability (e.g., modularization) as well as bundling of disparate components into a new innovation (e.g., integration[5]) vis-à-vis how these components are linked to the rest of the product architecture have to be considered. The following key elements define the degree of modularization embedded in product architectures: components, interfaces, degree of coupling, and substitutability, as shown in Figure 1.
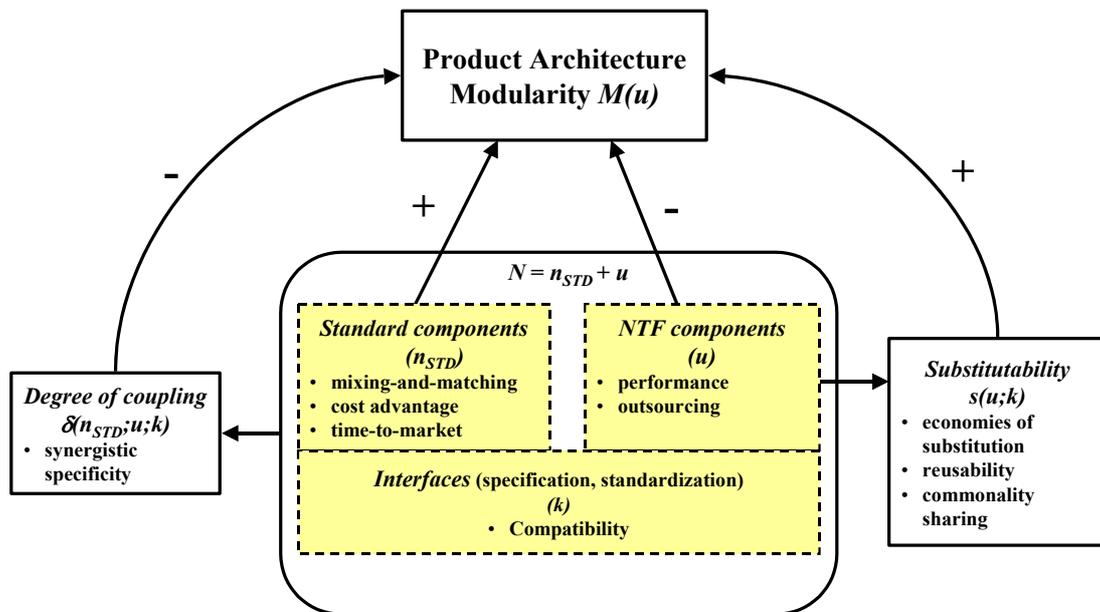

Figure 1. Key Elements of Product Architecture Modularity.

[5] Part integration is a common motive for integral product architectures (Ulrich & Eppinger, 1995; Ulrich, Sartorius, Pearson & Jakiela, 1993) and refers to (Ulrich & Ellison, 1999:647): "the combination of multiple parts into one contiguous part. [It] minimizes the use of material and space associated with component interfaces, and may improve geometric precision, but compromises the one-to-one mapping from functional elements to components."

Components

A *component* is defined as a physically distinct portion of the product that embodies a core design concept (Clark, 1985) and performs a well-defined function (Henderson & Clark, 1990). The selection of components reflects strategic choices made by firms. There are many ways of categorizing components, depending on the purpose of the study. For many firms, components are classified as either standard or new-to-the-firm (NTF), depending on whether the firm has had prior knowledge and application of these components in previous or existing product architectures. Information on these components (e.g., total number of components, component description, and component unit costs) is often listed in bill-or-materials (BOMs).

Standard components refer to components that have been used in previous or existing architectural designs by the firm (i.e. carried over components) or components that are available from firm's library of components (i.e. qualified components). A subset of standard components is the off-the-shelf or generic parts. Due to previous experience with standard components, interface compatibility issues can be assessed quickly without incurring expensive testing costs. Product architectures comprised of standard components are often considered modular product architectures with low synergistic specificity and high degree of recombinability (Schilling, 2000). According to Ulrich & Ellison (1999) some benefits for firms to select an existing component include: (1) to minimize investment – the reuse of existing components avoids significant additional investment in product development and tooling; (2) to exploit economies of scale from production volume; and (3) to preserve organizational focus leading to specialization and the development of capabilities.

New-to-the-firm (NTF) components, on the other hand, refer to product-specific components that are introduced to the firm for the first time. Because prior knowledge about how NTF components interact with other components is limited, NTF components are assumed to contain higher technological risks than standard components. Interface compatibility issues with other components within the product architecture have to be tested and re-evaluated regularly, and sometimes this process can be costly and time consuming[6]. Often the risks are well justified by the technical superiority of these components, significantly improving the overall performance of the product architecture. The use of NTF components is strategic in nature because the integration of NTF components into product architectures prevents imitation by the competitors, thus creating competitive advantages for the firm, at least in the short-run. But too many NTF components may delay product development lead time and increase the technological complexity of the product architecture, as a system achieves greater functionality by the strong interdependence shared among components, or high synergistic specificity (Schilling, 2000). Designing NTF components allows firms to (Ulrich & Ellison, 1999): (1) maximize product performance with respect to holistic customer requirements, that is, requirements that arise in a complex way from most of the components of a product; (2) minimize the size and mass of a product – the desire for part integration in order to conserve mass and size gives rise to an integral architecture which implies that components will have

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[6] In a study of multi-project management in the automobile industry, Cusumano & Nobeoka (1998) found that developing components new to the firm requires extra time for concept generation, producing prototypes, and testing that companies can not do in parallel, hence requiring both a longer lead time and more engineering hours.

to be redesigned; and (3) minimize the variable costs of production – variables are largely determined by component mass and size.

Interfaces

Interfaces are linkages shared among components, modules, and subsystems of a given product architecture. Interface specifications define the protocol for the fundamental interactions across all components comprising a technological system[7]. Modularization intentionally creates a high degree of independence between component designs by standardizing component interface specifications (Sanchez & Mahoney, 1996). The degree to which interfaces are standardized and specified defines the compatibility between components, subsequently the degree of modularity. Standard components have well specified and standardized interfaces, making it possible to gain from mixing-and-matching of components, savings from incorporation costs (e.g., testing costs, sourcing costs, etc.), and reduced time-to-market lead time (e.g. component availability from various suppliers, prior technological knowledge, etc.). Hence product architectures comprised of standard components are assumed to be modular. Conversely, because NTF components are introduced to the firm for the first time, they often do not have well-specified and standardized interfaces, hence increasing compatibility problems with other components. Consequently, introduction of NTF components into product architectures hinders modularity freedom. It seems plausible to assume that the higher the composition of standard components (or the lower the composition of NTF

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[7] Typical interface specifications of a product architecture at the detailed engineering level, for example, include the tolerance specification of the components with respect to manufacturing processes (such as lead diameter and type of lead bend of capacitors, which can be radial or axial), maximum heat dissipation, housing dimensions, etc.

components), the more modular is the product architecture. Interface specification of NTF components is dependent on technological innovation available in the market. For instance, if the NTF component is new to the industry, its interface specification is most likely to be ill specified. However, when the NTF component is unique only to the firm, its interface specification is generally well defined within the industry, but not standardized within the firm. Only when interface specification of NTF components become well specified and standardized within the firm that a NTF component becomes a standard component. According to Ulrich (1995), standardization arises when: (a) a component implements commonly useful functions; and (b) the interface to the component is identical across more than one different product.

Proposition 1. The percentage of NTF components has a negative effect on the degree of modularization embedded in product architectures.

Degree of Coupling

Product performance is governed by many components that are related to one another in a complex, interdependent fashion. Components are typically characterized by many design parameters, which may need to be tuned arbitrarily in order to maximize overall product performance (Ulrich & Ellison, 1999). The way in which components are linked with one another creates a certain degree of coupling, which indicates the relative 'criticalness' of components in the architecture. A component that is dependent on many other components (e.g., many interfaces) for functionality would impose high degree of coupling. For example, a microprocessor (a component) in a motherboard (a PC sub-system) would be considered a critical part based on the number of interfaces shared with other components. In order for a microprocessor to

function properly, it has to interface directly with a number of components, easily ranging from 56 to over 200 interfaces. Conversely, a capacitor would present lower degree of coupling than microprocessors. Typically, capacitors require two interfaces for functionality, a cathode and an anode.

We can imagine that product architectures with a great percentage of critical components may not be easily decomposed. The degree of coupling is similar of what Schilling (2000) and Schilling & Steensma (2001) refer to as 'synergistic specificity.' Product architectures with high degree of coupling among the components exhibit high 'synergistic specificity' as the strong interdependence shared among components inhibits recombination, separability, and substitution of components, hence preventing the architecture to shift into a more modular one. Depending on the product architecture configuration, often decided by the engineers, the combined effect of components and interfaces dictates the degree of synergistic specificity of the product architecture. In integral product architectures, one would expect to find components requiring more interfaces with other components for functionality, hence the product architecture is more tightly coupled (or has higher degree of coupling). Product architectures with low degree of coupling, on the other hand, have components that are relative independent of each other, or it may be possible to encapsulate the functions of particular component and employ a standard interface between them that enables them to contact with little or no loss of performance (Garud & Kumaraswamy, 1995; Sanchez & Mahoney, 1996; Schilling & Steensma, 2001). When we analyze similar product architectures (e.g. Parnasonic versus Sony televisions) in terms of their components and respective interfaces, we would likely find that the product architectures have their own configuration as to how components are linked with each other. Some product architectures have more components but few

interfaces, while others fewer components but requiring more interfaces for functionality.

Proposition 2. The degree of coupling has a negative effect on the degree of modularization embedded in product architectures.

Substitutability

Another crucial element of product architecture modularity is substitutability[8]. Garud & Kumaraswamy (1995) use the term 'substitution' to suggest that technological progress may be achieved by substituting certain components of a technological system while reusing others, hence taking the advantages of economies of substitution. Economies of substitution exist when the cost of designing a high-performance system through the partial retention of existing components is lower than designing the system afresh. With economies of substitution, firms can reduce product development time, leverage past investment, and provide customers with continuity. Components have to be compatible in order to be substitutable. While standard components facilitate component reusability, NTF components improve the technological performance of the upgraded product architecture. The challenge is to design product architectures with desirable combination of standard and NTF

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[8] According to Dogramaci (1979), the issue of substitutability in product design decisions has been studied extensively by industrial engineering scholars under the terms of 'modular production concept' (Starr, 1965), the 'commonality problem' (Rutenberg, 1971; Rutenberg & Shaftel, 1971; Moscato, 1976; Dogramaci, 1979; Collier, 1981; Collier, 1982; Baker, Magazine & Nuttle, 1986), and the 'assortment problem' (Sadowski, 1959; Wolfson, 1965; Jackson and Zerbe, 1968; Swanson, 1970; Pentico, 1976; Walters, 1976). In 'modular production concept (Starr, 1965), for instance, substitutability refers to interchangeability of parts, or the combinatorial capacities to design and manufacture parts that can be combined (or mixed-and-matched) in numerous ways.

components to gain from economies of substitution. NTF components may not fit or interact well with existing components, thereby compromising system integrity. Substitutability of NTF components also captures the customization of product architectures. For instance, Nishiguchi (1993) found that when a U.S. supplier develops a component for a U.S. customer, the same auto component is fitted into 8.3 car models. In contrast, Japanese suppliers sell the identical part for only 5.7 models, indicating higher customization of Japanese auto parts for car models.

Another aspect of substitutability is component sharing (i.e. using the same version of a component across multiple products) which is a product-based strategy that depends on the fact that families of similar products have similar components (Fisher et al., 1999). Many firms view component sharing as a way to offer high variety in the market place while retaining low variety in their operations. Component sharing of NTF components is especially critical. As articulated by Fisher et al. (1999:299): "Because each new and unique component must be designed and tested, component sharing can reduce the cost of product development. Each new and unique component generally also requires an investment in tooling or other fixed costs of production. Therefore component sharing may also reduce the required production investment associated with a new product." The managerial challenge is how to provide the high degree of uniqueness that seems necessary for competitive success while retaining the scale economies required for low cost. Firms generally do not introduce radical product designs to the market every time, rather incremental product designs are more often observed. We would imagine that a firm saves costs by using standard components in product architecture designs, than if it were to use NTF components. If a firm is to invest the time and effort to incorporate NTF components into the product

design, the value for using these components are often justified by their superior performance, especially if they can be shared across product families.

Proposition 3. The substitutability of new-to-the-firm components has a positive effect on the degree of modularization embedded given product architectures.

OPERATIONALIZING MODULARITY OF PRODUCT ARCHITECTURES

Many studies on modularity are qualitative and exploratory in nature (cf. Baldwin & Clark, 1997; Christensen & Rosenbloom, 1995; Garud & Kumaraswamy, 1993, 1995; Hsuan, 1999; Lundqvist, Sundgreen & Trygg, 1996; Robertson & Ulrich, 1998; Sanchez & Mahoney, 1996). The few quantitative study on modularity typically applies optimization models to address manufacturing issues (cf. Baker et al., 1986; Dogramaci, 1979; Emmons & Tedesco, 1971; Evans, 1963; Passy, 1970; Rutenberg & Shaftel, 1971). These models (applying mainly linear programming and dynamic programming techniques to solve the modular production, commonality, and assortment problems), although sophisticated, are confined to production constraints and offer limited insight and guidance as to how firms can measure the degree of modularity embedded in product architectures. One of the challenges faced by research in modularization in NPD is the difficulty with the operationalization of various dimensions into measurable or testable hypothesis. Statistical methodologies seem to be the preferred approach to link theory and practice in many economic organization and strategy literatures. However statistical methods may not capture the intrinsic characteristics of product architectures, which are often firm specific. Data accessibility and collection may also present a problem since product architecture related information is often proprietary.

Recently, there are a handful of studies that focus on measuring modularity, mainly developed by Ulrich and colleagues. For instance, Ulrich & Pearson (1998) use product archeology as an approach to gather objective data for product development research. The purpose is to measure the manufacturing content (i.e. the attributes of the design that drive costs). Fisher et al. (1999) apply a mathematical model to examine variation in component sharing practice and to identify factors that can explain the variation. In order to estimate the impact of different design alternatives on the net economic benefit of a product, Ulrich et al. (1993) apply an economic model to illustrate the relationships between design for manufacturability (DFM), lead time, and profits. These approaches support and complement the research approach presented in this paper, such as extracting information from BOM to measure component standardization (Collier, 1981, 1982; Ulrich & Ellison, 1999), examining the variation in component sharing (Fisher et al., 1999), designing product specific components (Ulrich & Ellison, 1999), and estimating the impact of design alternatives (Ulrich et al., 1993).

Modularization Function

In order to capture the complexity embedded in product architectures, a mathematical model termed *modularization function* (Equation 1), is applied. The following key factors define the degree of modularity [$M(u)$] with respect to the number of NTF components [u] embedded in a given product architecture: components [N and n], degree of coupling [δ], and substitutability [s]. See Appendix A for the formulation of modularization function, and Mikkola (2003) and Mikkola & Gassmann (2003) for the application of the modularization function with real world product architectures.

$$M(u) = e^{-u^2/2Ns\delta}$$
(Equation 1)

Degree of coupling and substitutability factor are a function of the number of components [n] and interfaces [k], as shown in Equation 2 and Equation 3:

$$\delta_{sub-system} = \delta_{average} = \frac{\sum_{i=1}^{I} \delta_i}{I} \quad \text{where} \quad \delta_i = \frac{\sum k_c}{n_c} \quad \text{(Equation 2)}$$

I = number of sub-systems

$$s = \frac{\text{no. of product families}}{k_{NTF}(\text{avg})} = \frac{\sum_{j=1}^{L} PF_j}{\frac{\sum_{i=1}^{K} k_{NTF}}{K}} \quad \text{(Equation 3)}$$

L = number of product families

K = total number of interfaces of NTF components

The modularization function is interpreted as follows. A given product architecture has N components that is the sum of standard components [n_{STD} or $N - u$] and NTF components [u]. The specific ways in which components are linked through interfaces [k] create a certain degree of coupling [δ], which is approximated as the average number of interfaces per component. The impact of substitutability of NTF components in product architecture modularity is captured through the 'substitutability factor' [s], which is estimated as the number of product families made possible by the average number of interfaces of NTF components [k_{NTF}] required for functionality. A perfect-modular product architecture [$M(u) = 1.0$] does not have any NTF components. NTF components that can be used across product families have higher substitutability factor (hence benefiting from economies of substitution, reusability, and commonality sharing) than NTF components that are dedicated to one specific product family, hence increasing the degree of modularization. The modularization function shows that the combined effect of the variables varies

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exponentially with any set of NTF components. Every time the composition of NTF is altered (such as with incremental innovations) the degree of modularity also varies. In many cases, the introduction of NTF components requires changes to other parts of the product architecture as well, hence changing the values of N and δ. If we simply assessed the degree of modularity based on the number of components (be standard or NTF) and ignored the effects of interfaces (captured in δ and s) we may overlook the impact of interfaces on product architecture modularity. Some general observations and managerial implications can be drawn from the modularization function, as illustrated in Figure 2. These implications are interpreted in terms of movements A, B, C, and D.
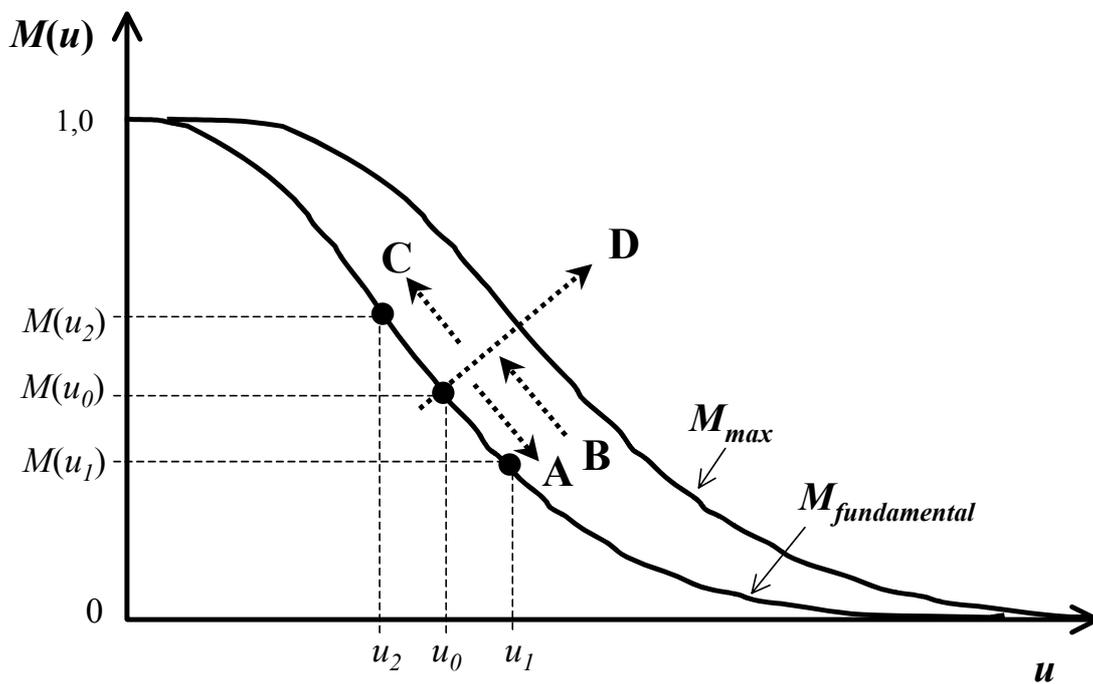

Figure 2. Dynamics of Product Architecture Modularity.

Movement A. The modularization function captures the firm's ability to incorporate NTF component into the new product architectures. Movement A indicates that an existing component is replaced by another component that is technologically more superior, such as with modular innovations. A modular innovation is treated as a NTF component that is introduced to the product architecture for the first time, assuming that all other components and interfaces remain unchanged. Whether the NTF component is to be produced by the firm itself or outsourced, movement A suggests that new manufacturing processes and tooling probably have to be implemented, which may be time consuming and expensive. Depending on the production volume, introduction of NTF components often requires changes in the firm's materials planning and production capacity. When the NTF component is outsourced, it has to be qualified and also has to comply with customer's requirements. Upgrading product architectures by introducing NTF components also implies that new promotion and other marketing strategies has to be revised. Assume that initially a product architecture has a degree of modularity $M(u_0)$. In order to upgrade this product architecture, a better component with superior technology is to replace an existing component without changing the other components (i.e. a modular innovation). When the modular innovation is introduced to the product architecture for the first time, it is treated as a NTF component (u_1), hence temporarily lowering the overall degree of modularity to $M(u_1)$, indicated by Movement A.

Movement B.   Over time, when the technological workings about the NTF component with the rest of the product architecture become standardized (that is, the component is qualified and listed in the component library as a standard component – and this may take years), then we would expect the product architecture to become more modular. This means that contract arrangements with suppliers and customers

are in place (i.e. purchasing volumes and prices are set). Production processes are 'frozen' in the sense that alterations to design and assembly processes (such as changing automation technology and respective tooling) cannot be done without going through official 'engineering changes' procedures.

Movement C. Movement C can take place under the conditions of part integration strategies. Many industries (such as bicycle, semiconductor, automotive, and elevator industries) are experiencing technological advancements through part integration in which multiple parts are combined into one contiguous part. For example, in 1995, Shimano gained market share in the U.S. by integrating traditionally modular components, particularly the drive train. The rear hub and cog set were integrated in a way that other brands of cogs and hubs were incompatible with Shimano's components. Shimano also integrated its shift levers into the braking system, requiring bicycle assemblers to purchase Shimano brake and shift levers as a single unit (Kerber, 1998). Although the common motivation for part integration is to benefit from integral product architectures, when devised incrementally and effectively it can still maintain the desired level of modularity. Under the modularization function framework, movement C takes place when part integration lowers the total number of NTF components while not exceeding the overall degree of coupling δ of the product architecture. In other words, the new contiguous part should be designed in a way that the number of interfaces required for functionality is minimized. Another situation that we may see movement C is through the substitutability factor. The more number of product families that can use the new contiguous part the higher the value of $M(u)$. Higher substitutability factor implies that both economies of scale (in in-house component production or in purchasing volume from suppliers) and scope (in customization and performance of product families) can be achieved.

Movement D. Movement D captures the amount of product variety and customization allowed by the product architecture. Every time a new architecture is revised a new modularization function is created. Sometimes best and worst case modularity functions can be generated, where $M_{fundamental}(u)$ indicates the basic configuration and $M(u)$ represents the most complex (both in composition of components and in customization) configuration. For example, elevators are considered modular systems, yet a great deal of customization (based on common product architectures) must also take place. This has direct implications for manufacturing performance. A firm's choice about product variety requires manufacturing plants to cope with a certain level of product mix complexity. Many studies indicate that there is a trade-off between product variety and manufacturing performance (Fisher & Ittner, 1999; Clark & Fujimoto, 1991; MacDuffie, Sethuraman & Fisher, 1996; Goldhar & Jelinek, 1983; Jaikumar, 1986; Panzar & Willig, 1977). According to (Fisher & Ittner, 1999:773), "greater product variety increases overhead by requiring more effort to create demand forecasts, greater inventory and material handling, more complex scheduling and task assignment, more frequent engineering changes, and increased supervisory requirements. Greater parts variety also implies lower volume per part, rising production costs. In addition, statistical process control becomes harder to perform when demand for parts is low and episodic, increasing quality problems."

DISCUSSIONS AND IMPLICATIONS

Practitioners as well as academics can gain insights into modularity management from the modularization function. The modularization function can be used as a framework to aid to examine leveraging forces behind NPD, manufacturing, and supply chain management policies of a firm through the key elements of product architectures. The function allows theoretical simulations (such as sensitivity, optimization, trade-off,

scenario analyses, etc.) to take place. It also enables researchers to theoretically test many causal linkages of the variables on the degree of modularity in product architectures. For managers, it can be used as a tool for communicating with the engineering, manufacturing, marketing, and purchasing functions. Changes in product architecture designs call for different strategies for managing production volume, manufacturing processes, amount of product variety, concurrent engineering, advertisement, etc. The modularization function can also be used to evaluate and compare competitors' product architectures through reverse engineering. It can also be used as a framework to link implications of product architecture modularity to theoretical discussions.

Theoretical Implications of Modularization Function

The modularization function can be interpreted from different theoretical perspectives. Here I extend the discussion to resource-based view (RBV) of the firm and transaction cost (TC) perspectives. RBV has been an important theory for understanding how competitive advantage within firms is achieved and sustained over time (Barney, 1991; Prahalad & Hamel, 1990; Teece, Pisano & Shuen, 1997; Wenerfelt, 1984; Peteraf, 1993). RBV basically focuses on costly-to-imitate attributes of the firm as sources of economic rent, and that those resources are heterogeneously distributed across firm, and that resource differences persist over time (Amit & Shoemaker, 1993; Mahoney & Pandian, 1992; Conner, 1991; Penrose, 1959, Wenerfelt, 1984). According to Barney (2001:645) the RBV framework recognizes that some resources and capabilities can only be developed over long periods of time (i.e. path dependence), because it may not always be clear how to develop these capabilities in the short to medium term (i.e. causal ambiguity), at least some resources and capabilities can not be bought and sold (i.e. social complexity), at least

some factors of production may be inelastic in supply (Dierickx & Cool, 1989; Barney, 1991).

Modularity management of product architectures can be viewed as the management of a firm's resources. The capabilities associated with product architecture designs take time and money to develop, and the subsequent market success (or failure) of the firm is dependent on the architecture's configuration (i.e. heterogeneity of resources and causal ambiguity), the extent to which certain technologies and components (i.e. resources and assets) are inimitable by competitors, and the management of resources that must be share with suppliers, especially when complementary assets (Teece, 1986) are considered. As the modularization function indicates, the constituent components and how these components are linked to one another determine the degree of modularity in product architectures. Product architecture strategies are often made concurrently with other organizational capabilities of the firm, making most product architectures idiosyncratic and extremely difficult to be imitated. Hence product architectures can be interpreted as firm-specific assets, in the sense that it is virtually impossible to find two competitive systems in the market with exactly the same product architectures with matching components and interface specifications.

In competitive markets, firms differ in their distinctive capabilities (Day, 1994) that are based on processes, involving the combination of physical resources and human collaboration that are repositories for firm's tacit and explicit knowledge (Olavarrieta & Ellinger, 1996). For many firms these distinctive capabilities are embedded in their organizational capabilities, which are reflected in their product architecture strategies. A product architecture that has a value of $M(u)$ close to 1.0, indicates that it is more

modular allowing for 'autonomous innovations'[9] to take place. Centralized virtual organization can manage the development and commercialization tasks efficiently. Information embedded in modular architectures are codified information in the sense that specifications that are captured in industry standards and design rules can often be transferred effectively within and across companies, hence not easily protected (Chesbrough & Teece, 1996). In order to create sustainable competitive advantage in product architecture designs, some sort of uniqueness that are difficult to be imitated by competitors (at least in the short run) must be devised. The number of NTF components in the modularization function captures this. As the number of NTF components increases (x-axis), the product architecture becomes more integral, indicated by a lower value of $M(u)$, which often favors towards the development of 'systemic innovations' (Chesbrough & Teece, 1996; Teece, 1996). Systemic innovations take place when the benefits of innovation can be realized only in conjunction with related, complementary innovations (often required by integral product architectures as well). These types of innovations require organizational members to be highly dependent of each other. In addition, information sharing and coordinated adjustments must be managed throughout an entire product system. Coordinating architectural innovations is particularly difficult when industry standards do not exist and must be pioneered. When an innovation depends on a series of interdependent innovations, independent companies (such as ones liked through arm's-length contracts) will not usually be able to coordinate themselves to knit those

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[9] 'Autonomous innovation' refers to innovation that can be pursued independently from other innovations, hence requiring little coordination among stages. Conversely, 'systemic innovation', that is, innovation that requires readjustment to other components of the system, would be more difficult in modular systems. Coordination of systemic innovation may be costly across markets, and makers of components may integrate vertically (Chesbrough & Teece, 1996; Teece, 1996).

innovations together (Chesbrough & Teece, 1996). Under the modularization function framework, autonomous innovations fit better with a high value of $M(u)$ while systemic innovation is better matched with product architectures with low value of $M(u)$.

A product architecture with an initial value of $M(u_0)$ indicates that it has a certain degree of coupling δ_0 and a substitutability factor of s_0. $M(u_0)$ reflects the firm's current heterogeneity of resources (i.e. composition of components) and routines (i.e. standardization of NPD and manufacturing processes). The combination of standard and NTF components in creating the product architecture over time creates some sort of 'dynamic capability' (Teece et al., 1997) for the firm. It reflects the firm's ability to integrate, build, and reconfigure internal competences (e.g., through reusing standard components or developing NTF components) and external competences (e.g., through outsourcing of NTF components and accessibility to complementary assets) to address rapidly changing environments. The ability for a firm to strategically develop product architectures more cost effectively and to generate unique product variants (with high substitutability factor) quicker than the competitors is a firm-specific capability. When a modular innovation is introduced sometime later (assuming that there are no changes in the relationships shared with the rest of the product architecture, that is, the variables N, δ_0, s_0 remain constant), we would expect Movement A to take place. In order for NTF components to become a standard component, it often needs to be qualified per firm's standard operating procedures vis-à-vis supplier's capabilities (if the component is outsourced), its interface specifications have to become well-specified in the context of the product architecture, and it has to work in concert with manufacturing capabilities of the firm. If a NTF component can be developed in a way that is non-tradable, non-imitable and non-substitutable, it can accrue rents for

the firm, especially when such component can also achieve economies of substitution. As the firm learns more about the compatibility issues of the NTF component, new routines become codified and adaptation takes place. Movements A and B [$M(u_0) \rightarrow M(u_1) \rightarrow M(u_0)$] indicate the dynamics NTF components.

Firms inevitably have to decide which NTF components to produce in-house and which ones to outsource to suppliers. From transaction cost perspective, the most efficient way to govern an exchange is through the cost of a governance mechanism and the threat to opportunism. A transaction occurs when a good or service is transferred between technologically separable stages (Williamson, 1999), and a key factor in supplanting market by internal organization is due to technological nonseparabilities (Alchian & Demsetz, 1972). When a system can be decomposed into loosely coupled arrangements, outsourcing decisions can be devised. TC explains that outsourcing decisions should be governed by specificity of the assets required to engage in development and production of the good. When assets are specific to an exchange, there are performance advantages (transaction cost savings) of integration that will act as a disincentive to use of more loosely coupled arrangements. Through specifying and standardizing the nature of an activity and the terms of exchange, a standard interface makes assets nonspecific (Schilling & Steensma, 2001). The outsourcing of a NTF component changes the firm's boundary and specific assets gives rise to bilateral dependence, which poses contractual hazards in the face of incomplete contracting and opportunism. Uniqueness of the assets involved in the relation or uncertainty on the outcomes increase the likelihood of opportunist behavior form the supplier, hence increasing the transaction costs of using market to secure production (Veloso & Fixon, 2001). From the product architecture perspective, the bilateral dependence is linked to the specification of the component to be outsourced,

which has implication for short- or long-term contracts. Although the modularization function does not distinguish between the types of outsourced components, the number of NTF components (x-axis) has direct implications for contractual arrangements and most effective governance mechanisms, which are dependent on the product architecture design strategies (y-axis). In a recent study on automotive industry, Dyer (1997) suggests that beyond minimizing transaction costs, governance influences transaction value by influencing the transactors' set of choices regarding the level of specialized assets that will be employed.

According to Garud & Kumaraswamy (1995), internalizing activities within a firm involves managerial and production costs. Managerial costs of coordination increase with the number of components produced in-house and with the number of stages required to produce a given component. Cognitive complexity faced by managers also increases, which at some point, it becomes more costly for a firm to undertake any more activities in-house than it is to delegate them to others. Novak & Eppinger (2001), for instance, argue that in-house production is more attractive when product complexity is high, as firms seek to capture the benefits of their investment in the skills needed to coordinate development and production of complex systems. Specifically, product complexity has three main elements (p. 189): (1) the number of product components to specify and produce; (2) the extent of interactions to manage between these components; and (3) the degree of product novelty. In-house production costs also increase when demand is low or uncertain, such as when the firm cannot justify production facilities that operate at a minimum efficient scale for each component. In this view, managerial and production costs are key forces for the disaggregation of activities. Under the modularization function framework, the most

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efficient governance mechanism to govern an exchange of perfect modular product architectures would be the market governance.

Limitations of the Modularization Function

The use of mathematical models involving differential equations, such the modularization function, is applicable for quantities that change continuously, and sometimes with functions that take on only discrete values can be treated as though they actually have derivatives and satisfy differential equations. The modularization function is one way of managing the complexity of modularity. It is best applied at analyzing complex systems (such as automobiles, airplanes, satellites, elevators, etc.), in which the number of components is enormous involving continuous incremental changes to both the process and the system itself affecting the component composition of a pre-defined product architecture. Similar trade-offs between modular and integral product architectures, arising from NTF components, exist for many complex systems in various industries. In order to compete, technology novelties are introduced continuously, often through incremental innovations, such as add-ons and upgrades that are based on present product architectures. These systems often have large number of components with a set of NTF components, which are shared across product families. Decomposition of the system into more manageable parts is one of the most attractive ways to manage the complexity of product designs. As long as the product architecture can be decomposed so that schematics and BOMs can be generated, the degree of modularity can be assessed with the modularization function. Modularization function consolidates the complexities of product architecture variation and customization into a simple formula, allowing managers as well as academic researchers to compare, simulate, and predict the implications of technological development on future generations of product architectures. The

modularization function may provide a good theory for studying complexity embedded in product architectures, although formulated is not statistically tested nor proven. We need to apply statistical methodologies to test the propositions. This would provide further validation as well as improve the robustness of the model.

APPENDIX A

It is assumed that there is a relationship between degree of modularization *M* and the number of NTF components *u*, *M* = *f*(*u*). The lower the number of NTF components, the higher the degree of modularization. Hence, a perfect-modular product architecture has no NTF components. The degree of modularization, *M*, decreases at a rate, *r*, that is proportional to the amount of modularization present with each set of NTF components, *u*. If *M* is the amount of modularization present in a given product architecture with any set of NTF components *u*, then as the number of NTF components vary, the amount of modularization will have changed by the amount of $\Delta M = rM$. In other words, for any unit change of NTF components ($\Delta u = 1$), the corresponding amount of modularization change ΔM is proportional to the initial level of modularization.

$$\Delta M = (-rM)\Delta u \quad \text{and} \quad r = \frac{b}{s\delta} = \frac{u/N}{s\delta} \quad 0 \le b \le 1.0$$

The factor *r* is the rate in which NTF components are averaged out across $s\delta$, which is the cumulative interface constraint effect of sub-systems, across product families.

$$\Delta M = (-rM)\Delta u = \left(-\frac{u/N}{s\delta}\right)M\Delta u$$

In differential equation form,

$$\frac{dM}{du} = -\frac{u}{Ns\delta}M \quad \text{or} \quad \frac{dM}{M} = -\frac{u}{Ns\delta}du$$

For any constant *r*, the solutions to the above differential equation are of the form:

$$M(u) = M_0 e^{-u^2/2Ns\delta}$$

Solve for the initial condition: $M(0) = M_0 = 1.0 \quad ==> \quad M(u) = e^{-u^2/2Ns\delta}$

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