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"Modularity in New Market Formation"

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Modular Architectures in the Marketing Process

Modular product architectures are being adopted as the basis for new product designs in a growing number of markets. In this article, the author explains how adoption of modular product architectures makes possible new kinds of processes for creating and realizing products, as well as new approaches to identifying and managing organizational knowledge used in product creation and realization. When managed strategically, modular product, process, and knowledge architectures enable firms to create greater product variety, introduce technologically improved products more rapidly, bring new products to market more quickly, and lower costs of product creation and realization. This article investigates the ways in which the strategic use of modular architectures can affect the marketing process. It explains ways in which modular architectures change the technologically determined possibilities for product creation and realization in the marketing process, create new market dynamics, and lead to new objectives and methods for the marketing process.

The *marketing process* is the set of activities through which organizations identify and exploit opportunities to serve consumer needs. In carrying out its activities, the marketing process functions through various technological systems[1] for identifying consumer needs and applying available technological means to create and realize products to serve those needs. These systems include the product designs, production processes, distribution channels, and service infrastructures that firms create, as well as the organization structures and interrelated knowledge assets that firms use in creating and realizing products. The technological systems used in the marketing process create an institutional context that strongly influences the pace and direction of change in markets and technologies (Robertson and Langlois 1995).

This article investigates the growing use of *modular* product, process, and knowledge architectures (PPKAs) as a new technological system for carrying out the marketing process. Modular architectures are represented here as a new kind of technological "deep structure" that makes possible significant innovations in the marketing process and is leading to new kinds of product strategies, organizational forms, and market dynamics in a growing number of product areas.

The discussion here suggests that the marketing process, as developed in theory and practice during the past three or four decades, has been influenced by some key implicit assumptions about what is technologically feasible and cost effective in identifying consumer preferences and designing, producing, distributing, and supporting products to serve those preferences. The adoption of modular PPKAs, however, is argued to effect significant changes in the technologically determined economics of the marketing process. When used effectively, modular architectures make it possible to create greater product variety, introduce technologically improved products more rapidly, bring new products to market more quickly, *and* undertake these initiatives at lower costs than ever before. As more firms learn how to use the flexibility and adaptability of modular architectures strategically, new market dynamics are being created that invite marketing researchers and professionals to reconceptualize both the objectives and the methods of the marketing process in modular product markets (Baldwin and Clark 1997; Sanchez and Collins 1998; Sanchez and Mahoney 1996). This article investigates these new dynamics, explains their origins in the strategic uses of modular architectures, and suggests some of their major implications for the marketing process.

The use of modular architectures in the marketing process is an emerging phenomenon. The characterizations of this phenomenon presented here therefore are drawn from case studies and observations of contemporary organizations. The concepts and characterizations of modular architectures developed and illustrated here are intended to suggest useful approaches and promising areas for further empirical investigation into the effects of modular architectures on competitive strategies, market dynamics, and technological change. In addition, this discussion should suggest several areas for further managerial development of the strategic uses of modular architectures in the marketing process.

This discussion is organized in the following way: The first section defines the concepts of PPKAs and describes their interrelationships in processes of product creation and realization. The second section explains how the PPKAs an organization uses both enable and constrain its marketing process. The third section defines the concept of modularity

[1]In this discussion, the term "technology" is used broadly to refer to all the tangible and intangible assets, human skills, and organizational capabilities involved in creating and realizing products.

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in architectures, contrasts modular product architectures with traditional "optimized" product designs, and discusses five properties of modular architectures and the strategic uses of those properties in the marketing process. The fourth section suggests several effects of modular architectures on the marketing process, including those on marketing research, marketing strategy, market development, supply chain and distribution channel design, and the boundaries of the marketing organization. Finally, the fifth section offers concluding comments on some of the key issues in developing and managing the marketing process in modular product markets.

PPKAs and Interrelationships

The designs of most products and processes are system designs that have general properties of decomposability into functional elements and interactions among those elements (Simon 1962). An *architecture* is a system design for which designers have specified (1) the way the overall functionalities of the product or process design are decomposed into individual functional components[2] (Baldwin and Clark 1997; Clark 1985) and (2) the ways in which the individual functional components interact to provide the overall functionalities of the system design. Component interactions generally are described by component interface specifications that define the inputs and outputs that cross the interfaces between interacting components (Sanchez 1996a).[3]

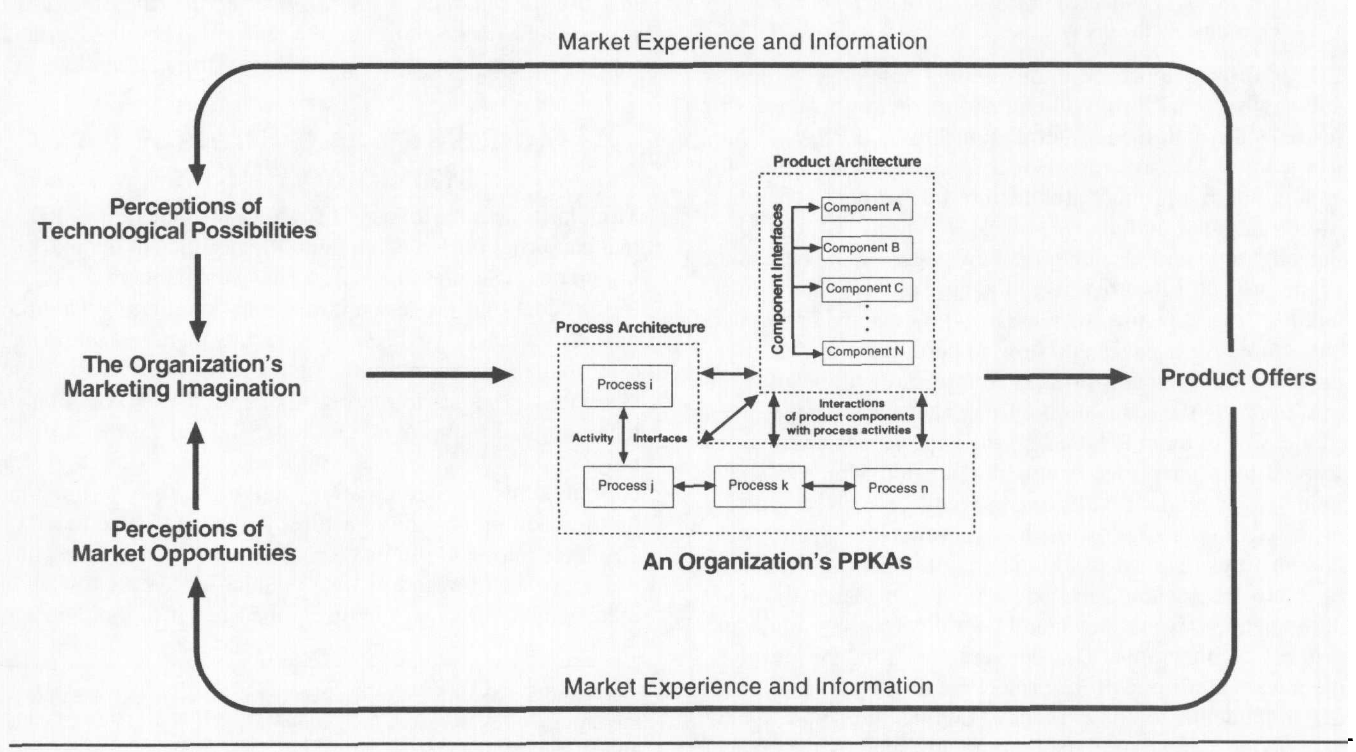
In the processes of creating and realizing products, organizations explicitly or implicitly create three kinds of architectures, whose interactions play an essential role in the marketing process: product architectures, process architectures, and knowledge architectures (see the central diagram in Figure 1).

A *product architecture* decomposes a product's overall functionalities into a product design composed of function-

[2]In technically complex products, the first stage of functional decomposition may be into subsystems (e.g., the electrical subsystem of an automobile) that perform a function in a product design, followed by a decomposition of subsystems into components (alternator, voltage regulator, battery, and so on). In simple products, functional decomposition may lead directly to individual parts that perform a functional role in the product design (e.g., the top and legs of a table). For simplicity in this discussion, the term "component" refers generally to the functional elements of a product that result from a functional decomposition process.

[3]Component interfaces in a product architecture include the following (Sanchez 1994*, 1999): (1) *attachment* interfaces that define how one component physically attaches to another; (2) *spatial* interfaces that define the physical space (dimensions and position) that a component occupies in relation to other components; (3) *transfer* interfaces that define the way one component transfers electrical or mechanical power, fluid, a bitstream, or other primary flow to another; (4) *control and communication* interfaces that define the way that one component informs another of its current state and the way that that other component communicates a signal to change the original component's current state; (5) *environmental* interfaces that define the effects, often unintended, that the presence or functioning of one component can have on the functioning of another (e.g., through the generation of heat, magnetic fields, vibrations, corrosive vapors, and so forth); (6) *ambient* interfaces that define the range of ambient use conditions (ambient temperature, humidity, elevation, and so on) in which a component is intended to perform; and (7) *user* interfaces that define specific ways in which users will interact with a product.

FIGURE 1
The Central Role of Product, Process, and Knowledge Architectures (PPKAs) in the Marketing Process



al components and component interface specifications that define how those components interact in the product design. Designs of personal computers (PCs), for example, are decomposed into components such as microprocessors, memory chips, monitors, keyboards, and disk drives, all of which interact in ways determined by the various interface specifications of the PC architecture. Many service products also can be decomposed into well-defined, interacting component functions. For example, dispensing cash through an automated teller machine requires a series of functional steps, each of which requires certain inputs and generates certain outputs that collectively allow the transaction to be completed.

Similarly, a *process architecture* decomposes the designs of an organization's processes into specific activities and defines the ways in which those activities interact in carrying out those processes. An organization's overall process architecture includes its activities for creating and realizing products and the interactions of those activities in the organization's marketing process.

An organization's *knowledge architecture* refers to the decomposition of the organization's knowledge into specific knowledge assets and the ways those knowledge assets interact in the organization's processes for creating and realizing products. An organization's knowledge architecture includes four essential and distinct kinds of knowledge an organization may have about the product and process architectures it creates and uses:

1. Knowledge of how a given functionality may be decomposed into specific product and process functions;
2. Knowledge of how product and process components function;
3. Knowledge of how its product and process components interact in product and process architectures; and
4. Knowledge of how each component in its product architecture interacts with each process component in its process architecture as the organization creates and realizes products.

Motorola's approach to developing new pager products and new systems for producing and marketing its pagers illustrates the nature and interrelationships of PPKAs. A project team of Motorola employees is given responsibility for creating both a product architecture for the next generation Motorola pager and a new process architecture for producing, shipping, and servicing the new pager. At the beginning of the project, Motorola gives the new project team a manual that describes how to create new product and process architectures for a pager and how to coordinate the architectures to ensure the new process architecture will be effective in supporting the realization of the pager. The manual given to the project team is based on the experiences and lessons learned by prior project teams that created Motorola's previous pager product and process architectures. The current project team must follow the basic approach to creating new architectures detailed in the manual but also must incorporate into the manual any new knowledge that it develops about better ways to create and coordinate new product and process architectures. The deliverables from the development team at the end of the project are therefore a new product architecture, a new process architecture, and a new knowledge architecture, the latter represented by the revised manual the team develops for creating and coordinating the next generation product and process architectures (Stroebel and Johnson 1993*).

Interactions of PPKAs and the Marketing Process

The role that PPKAs play in the marketing process is suggested in Figure 1. The market experience and information an organization gathers through marketing its current product offers shape its perceptions of technological possibilities and market opportunities. These perceptions drive the organization's marketing imagination. Product, process, and knowledge architectures are the technological means by which an organization creates and realizes the product offers it can imagine.

The central position of the diagram representing PPKAs in Figure 1 suggests the central role that they play in sustaining a "virtuous circle" of value-generating product creation and realization in a successful marketing process. In the short term, an organization's current product and process architectures determine the product offers the organization can bring to its markets. In the long term, an organization's knowledge about how to create new product and process architectures (i.e., its knowledge architecture) determines the new product and process architectures it can create to bring new kinds of product offers to market. Thus, at any point in time, an organization's PPKAs act as both platforms that enable and bottlenecks that constrain the organization's ability to transform its perceptions of technological possibilities and market opportunities into new product offers. Collectively, the PPKAs of firms in an industry determine the speed, direction, and scope of the technological and market changes in that industry.

The next section considers the ways in which the strategic use of modular PPKAs is affecting the marketing process and leading to new dynamics of technological and market change in a growing number of product markets.

Modularity as a Strategy for Managing PPKAs

Modularity is a multifaceted strategy for managing PPKAs that can bring important strategic flexibilities to the marketing process (Sanchez 1995a). As a design strategy for creating product and process architectures, modularity simultaneously can increase the product variety an organization can offer to markets, decrease the time and resources required to bring new products to market, speed up the introduction of technologically improved products, and reduce the costs of new product development. As a development strategy for coordinating product creation activities, use of modular product and process architectures helps extend the reach of an organization's product creation and other marketing processes well beyond its own boundaries. As a knowledge management strategy, the disciplined use of a modular ap-

*Authors were limited in the number of references used in text, therefore, those references marked with an * are available at www.ama.org/pubs/jm and at www.msi.org.

proach to creating product and process architectures can help identify the knowledge assets an organization has, as well as opportunities for developing strategically valuable new knowledge that can improve the effectiveness and reach of the organization's marketing process. Because of these strategic benefits, the subsequent discussion suggests that modular PPKAs are becoming a new dominant logic for supporting the marketing process in many product markets (Prahalad and Bettis 1986*; Sanchez 1995a).

The following discussion defines modularity, contrasts the modular approach for creating architectures to traditional processes for creating "optimized" product designs, and considers several distinctive properties of modular PPKAs and their strategic uses in the marketing process.

Modularity in Architectures

Modularity is created in an architecture when the interfaces between functional components are standardized (i.e., not allowed to change over some period of time) and specified to allow the substitution of a range of variations in components into the product architecture without requiring changes in the designs of other components (Garud and Kumaraswamy 1995; Sanchez and Mahoney 1996). Familiar examples of modular product architectures include audio and video components such as stereo amplifiers and compact disc players that have "plug-and-play" connectivity among models made by various manufacturers (Langlois and Robertson 1992). Another familiar example is the PC, which typically allows the substitution of variations in disk drives, memory cards, monitors, keyboards, and other components within the PC architecture. Indeed, much of the conceptual development of modularity as a design strategy has taken place in the computer hardware and software industries (Baldwin and Clark 1997; Myers 1975*; Page-Jones 1988*; Parnas 1972*; Parnas, Clements, and Weiss 1985*; Steffens 1994*).

Modular Product Architectures Versus Traditional Optimized Product Designs

The distinctive nature of a modular strategy for creating product architectures may be clarified by comparing its objectives and methods with those of the optimizing approach to product design that traditionally has been used in marketing processes.

A traditional optimizing design process begins with a description of the desired attributes and target cost for a new product. The objective of product designers is then to create an optimized product design that provides either (1) a defined set of attributes and performance levels at the lowest possible cost or (2) the highest possible performance levels for the set of attributes achievable within the constraint of the target cost (Alexander 1964*; Marples 1961*). To achieve these objectives, product designers typically create a complex product design that incorporates assemblies of interdependent functional components whose designs have been integrated to achieve the lowest possible cost or the highest possible level of performance for the product (Ulrich and Seering 1995). Because many alternative decompositions and interrelationships of functional components may be possible in the component integration process, development of optimized product designs is generally an iterative, recursive process that goes through many cycles of integrating, testing, and fine-tuning alternative component designs and combinations. An optimizing design process generally ends when a product design eventually is achieved that provides an acceptable combination of performance and cost.

The output of an optimizing product design process is typically a product architecture in which the integration of components has created assemblies of tightly coupled component designs (Orton and Weick 1990; Sanchez and Mahoney 1996). Integrated component designs are tightly coupled in the sense that a change in the design of one component within an integrated assembly of components will require compensating changes in the designs of other components in the assembly. Thus, making changes in one tightly coupled component within an optimized product architecture typically precipitates a chain reaction of design changes in other components, each of which may precipitate changes in other component designs, and so on. As a result, the tightly coupled component designs in an optimized product architecture often create a complex architecture that is difficult, costly, and time-consuming to modify.

In contrast, because the component interfaces in a modular product architecture are intentionally standardized and specified to allow the substitution of a range of variations in components into the architecture without requiring changes in the designs of other components, modular product architectures create a system of loosely coupled component designs.[4] Because the loosely coupled component designs in a modular architecture can be changed in various ways without having to make compensating changes in other component designs, modular architectures are intrinsically more flexible and adaptable than optimized architectures based on tightly coupled component designs.[5]

Properties and Strategic Uses of Modular Architectures in the Marketing Process

Several properties of modular architectures result from the loose coupling of component designs and make possible some innovative strategic uses of modular PPKAs in the marketing process. Table 1 summarizes these properties, derives strategic uses of modular PPKAs, and provides examples of firms using modular architectures strategically in their marketing processes.

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[4]The properties of being tightly or loosely coupled apply to component designs in this discussion, not necessarily to the physical components themselves. This important distinction can be illustrated by the example of a PC, for which various designs for a hard disk drive can be substituted into the product architecture (indicating a loose coupling of component designs in the product architecture). However, the functioning of a hard disk drive installed in the computer is necessary to the physical functioning of other components in the computer (indicating a tight coupling of the physical components in the product itself). In all cases in this article, the discussion of tight coupling and loose coupling applies to component designs, but the single word "component" sometimes is used for brevity in discussing component designs.

[5]Modular architectures based on loosely coupled components correspond to Simon's (1962) description of "nearly decomposable" systems with high levels of adaptability and survivability (Sanchez and Mahoney 1996).

TABLE 1
Properties, Strategic Uses, and Examples of Modular Product, Process, and Knowledge Architectures

Properties and Strategic Uses of Modular PPKAs	Examples of Strategic Uses of Modular PPKAs
1. Modularity enables the leveraging of product variations by substitution of component variations	
(a) Product variations can be created at low cost by mixing and matching component variations. The reduced cost of leveraging greater product variety can be used to •explore consumer preferences through real-time market research, •increase market segmentation, •saturate profitable regions of product space, and •support modular forms of mass customization. (b) Improved products can be brought to market quickly by substituting new components. (c) Switching among product variations improves management of demand cycles and uncertainty.	Sony uses five modular architectures to leverage 160 product variations in the U.S. market between 1980 and 1990 (Sanderson and Uzumeri 1997) Motorola offers 20,000,000 modular pager variations (Stroebel and Johnson 1993*) Object-oriented programming develops "object" modules that can be combined to create customized applications programs (Cusumano 1991*) National Bicycle of Japan uses a modular architecture to provide bicycles customized to the size and body proportions of individual customers (Kotha 1995*) GE Fanuc Automation offers "infinitely configurable" factory automation systems based on modular architectures (Sanchez and Collins 1998)
2. Modularity helps contain change by enabling common components to be used within and across product lines	
(a) Decoupling of components accommodates differential rates of technology development. (b) Reuse of common components within and across product lines reduces costs by •reusing existing component designs, •lowering costs through learning curve effects, •increasing scale of component production, •increasing buyer power for common components, •reducing component variety and inventories, and •reducing costs of product support. (c) Reuse of component designs helps improve component reliability. (d) Containment of change enables "late point" differentiation of products. (e) Containing parts that require replacement in easily changed components improves design of self-diagnostics and reduces service infrastructure requirements.	Sony's modular design for the HandyCam camera allows improved versions of key components to be introduced as they became available (Sanchez 1994*) Black-and-Decker redesigns its global lines of power tools to maximize commonality of cost-intensive components, leading to significant cost reductions (Utterback 1994*) Ford's modular V-8 engine architecture leverages many engine variations while maintaining at least 75% commonality of components (*Automotive Industries* 1994*) Boeing and Airbus use common wing, nose, and tail components in families of aircraft with different passenger/freight capacities (March 1990*; Woolsey 1994*) Hewlett-Packard adds the components that differentiate its products for local market requirements in its regional distribution centers just before shipment to retail dealers (Lee, Billington, and Carter 1993*) Canon consolidates all parts that need periodic replacement in a modular cartridge that users of its Personal Copier easily can replace themselves (Yamanouchi 1989*)
3. Modularity facilitates decoupling technology development and product development, enabling concurrent and distributed component development processes	
(a) Removal of technological uncertainty from product development process improves predictability of product development outcomes and timing. (b) Concurrent development of components increases the efficiency of component development and speed to market. (c) Subcontracting for component development, which •allows access to larger pool of component development capabilities in other firms, resulting in more variety-enhancing and high-performing components; •reduces initial investment to develop new products; •reduces technical and management resources needed to develop new products; and •reduces costs of product support.	Chrysler decomposes its new car platforms into 28 subsystems and defines interfaces ("hard points") between subsystems. Modularization of its product architectures permits •concurrent development of subsystems, reducing development cycles to 30 months or less; •increased component development activities carried out by component suppliers; •reduced investments required by Chrysler to develop each new car (Holmes 1995*). Chrysler improves the predictability of development milestone dates and new model introduction dates by adopting only component designs for which suppliers are "process capable now" (Herlitz 1997*)
4. Modularity enables the loose coupling of component designs and thereby creates loosely coupled knowledge domains	
(a) Reduced complexity of architectures improves efficiency and speed of technological learning. (b) Decoupling of component designs facilitates innovations in components. (c) Industry standard modular architectures create positive network externalities in technological learning and stimulate market learning.	Modular architectures improve Cummins Engine Co.'s ability to specify and control the performance characteristics of key engine components and subsystems (Venkatesan 1992) Modular architectures for PCs facilitate high rates of innovation in component technologies (Garud and Kumaraswamy 1993*; Steffens 1994*)

Leveraging product variations by substituting modular component variations. In modular strategies for creating product architectures, each product function or feature believed to be a significant source of product differentiation is embodied (as nearly as possible) in a single modular component or subsystem of components. The loose coupling of components in a modular architecture then enables the substitution of component variations into the architecture to create product variations based on different combinations of component-based functionalities, features, and performance levels. In this way, a modular product architecture can be used as a flexible platform for leveraging a potentially large number of variations on a product concept (Gilmore and Pine 1997*; Myer and Utterback 1993*; Robertson and Ulrich 1998*). This flexibility of modular product architectures may be used strategically to increase the number of product variations offered in the marketing process, increase the speed with which improved products can be brought to market, improve the management of demand uncertainty for specific product variations, and improve planning for future generations of products.

Creating increased product variety by mixing and matching component variations. Variations in modular components can be mixed and matched within a modular product architecture to create product variations with different bundles of component-based functionalities, features, and performance levels (Sanderson and Uzumeri 1997). For example, a simple modular product composed of four components, each of which is available in three variations, could be used to leverage $3^4 = 81$ product variations based on different combinations of component variations.[6] Not all the resulting product variations would necessarily be practical or appealing to consumers, but at least some combinations of component variations may provide sets of component-based functionalities, features, and performance levels that appeal strongly to consumers with certain kinds of preferences.

Compared with the difficulty, cost, and time required to introduce component variations into optimized product designs with tightly coupled components, the strategically designed flexibility to leverage product variations quickly and inexpensively by mixing and matching component variations in a modular product architecture creates several new possibilities for the marketing process.

First, leveraging product variations from modular product architectures at low incremental costs makes it possible to explore consumer preferences through real-time market research, a process in which small lots of new product variations (based on new combinations of modular components) are introduced to test consumers' reactions to various combinations of functions, features, and performance levels (Sanchez and Sudharshan 1993). Both Sony and Nike, for example, operate "antenna shops" in major cities, where they test-market a changing array of new modular product variations. Real-time sales figures, combined with direct observation of consumer reactions, provide fast feedback on consumer reactions to new product variations.

Second, the ability to leverage many different bundles of component-based functions, features, and performance levels from a modular architecture helps a marketing organization increase the extent of market segmentation it can support with a given level of product creation resources. By using the flexibility of a modular product architecture to leverage more product variations, a marketing organization can develop more detailed knowledge of consumer preferences for that product. This deeper knowledge of consumer preferences then may enable definition of new or modified product architectures that more effectively can serve the preferences of newly discovered market segments. After gaining insights into consumer reactions to product variations leveraged from its initial Walkman product architecture, for example, Sony subsequently developed a "downmarket" modular architecture intended to accommodate only the core components and functionalities of the Walkman product concept, as well as an enlarged modular architecture intended to accommodate new component-based features in a range of "upmarket" models. Thus, the flexibility to test markets with many product variations leveraged from modular product architectures may support more rapid and extensive marketing research and greater segmentation of markets.

Third, when a firm discovers the product variations most appreciated by consumers in a given market segment, more related product variations can be leveraged to saturate the most profitable regions of product space, leaving little or no unoccupied profitable product space to attract competitors.

Fourth, mixing and matching modular components to leverage product variations also is used in processes for mass customization[7] of products (Gilmore and Pine 1997*; Pine 1992).

Greater speed to market with improved products. Modular product architectures may be designed to accommodate both currently available components and technologically improved components that are expected to become available during the intended lifetime of a modular product architecture. Designing in the flexibility to substitute improved components into a modular product architecture makes pos-

[6]When even a modest number of component variations is available for substitution into a modular product architecture, the number of product variations that can be configured by combining different component variations can reach into the millions. In the general case, a modular product architecture composed of x functional components (a, b, ... x), each of which is available in several variations that can be substituted into the product architecture, $\{a_1 \ldots a_i, b_1 \ldots b_j, \ldots x_1 \ldots x_n\}$, will yield $\{i \times j \times \ldots n\}$ product variations. Thus, a large number of product variations may be obtained from a relatively simple product architecture decomposed into a few components that are available in a limited number of variations. A product architecture decomposed into 10 components, each of which is available in 10 variations, would yield $10^{10} = 10{,}000{,}000{,}000$ product variations, more than enough to create a different product variation for every person on earth.

[7]Modular architectures can support the configuration and delivery of customized combinations of component variations to individual customers, though not necessarily the customization of individual components for individual customers. Firms such as Dell Computer, for example, configure mass-customized computer systems on the basis of combinations of components selected by customers from a menu of available component variations.

sible the rapid introduction of improved product variations as soon as improved components become available. Many PCs, for example, now use motherboard (printed circuit board) architectures that have modular mounting sockets to enable the substitution of improved microprocessors as soon as they become available. When designed in this way, modular product architectures can accelerate substantially the introduction of new technologies into the marketing process by rapidly incorporating new components based on new or improved technologies.

Improved management of demand cycles and uncertainty. When demand for variations in products is subject to cycles or uncertainty about demand levels, the ability to shift production quickly to the modular product variations currently in greatest demand can improve the efficiency and profitability of the marketing process.

Improved planning for future products. Processes for planning next generation product and process architectures provide a structured, market-driven framework in which the results of both traditional and real-time marketing research can be used to define the range of consumer preferences that should be served by a next generation product architecture, as well as the technological capabilities needed to create the modular components required in the next generation architecture. Planning for future generation product architectures thus provides a structured framework for integrating long-term market and technology trends, identifying new kinds of components desired for future products, and defining the new technological capabilities needed to create new kinds of components and architectures.

Strategic partitioning of architectures to contain change and variety in components. A modular design strategy may use the loose coupling of components in a modular architecture to partition the architecture into (1) components whose designs will be changed frequently for strategic reasons and (2) components whose designs will be held constant for strategic reasons. The strategic partitioning of a modular architecture into changeable and stable components may be used to accommodate differential rates of technological change in various components, reduce product costs by increasing use of common components within and across product lines, improve the reliability of key components, support late-point differentiation of products, and reduce the service infrastructure required to support a product.

Accommodating differential rates of technological change. Different kinds of components are often subject to different rates of technological change. Strategic partitioning of a modular architecture may enable those component designs subject to high rates of technological change to be developed and introduced into a product architecture independently of other components whose technologies and designs do not change frequently. Strategic partitioning therefore may minimize the cost and time required to incorporate technological advances into product designs by focusing design resources on developing new designs for technologically dynamic components while avoiding redesigns of components that are not subject to significant technological change. Designs of components that are technologically stable may be used throughout the lifetime of a current architecture or even reused in subsequent generations of architectures.

Reducing product costs by increasing use of common components in product variations. A modular architecture also may be partitioned strategically to create loose coupling between (1) components that are sources of differentiation and are varied intentionally to create product variations and (2) components whose functions are required in all product variations or are transparent to customers and thus can be used in common across many product variations. When common components that are not sources of perceived variety in products can be insulated from changes in the components used to differentiate products, the increased ability to use common components in more product variations can lead to significant cost reductions.

Reusing common component designs lowers the development costs of new architectures and new product variations. Reusing the same component in multiple product variations also increases the quantities required for that component and may reduce costs through increased economies of scale or increased buying power for outsourced components. Continuing production of a component through more than one generation of product architecture may reduce costs further through cumulative economies of learning (experience curve effects). Use of common components also reduces costs of component inventories.

Improving the reliability of key components through reuse of component designs. Strategic partitioning that increases reuse of modular component designs over a period of time may lead to incremental improvements in materials and processes that improve the reliability of those components. Improved reliability of key components may lead to greater consumer satisfaction and reduced service and claims costs.

Supporting late-point differentiation of products. Strategic partitioning also may enable creation of a "universal chassis" that incorporates all the components used in common across various product models. The universal chassis then may be mass-produced, and component variations that differentiate product models can be added at a late point in production or distribution. Use of a universal chassis may reduce costs further by reducing the variety of parts that must be inventoried and handled in assembly processes. Similarly, when component variations that differentiate products can be added to a universal chassis at a late point in distribution channels, costs of inventorying and distributing product variations can be reduced.

Reducing service infrastructure requirements. Strategic partitioning of modular architectures also may reduce service requirements for products and thereby reduce the costs of the service infrastructures needed to support the marketing process. Strategic use of common components across product lines and reuse of components across generations of product architectures may reduce both the variety of replacement parts that must be inventoried and the staff training required to service products. The reduced technical complexity of modular product designs also may facilitate the design of self-diagnostic capabilities in products that reduce the need for technically skilled service staff. When components that need periodic replacement can be designed as easy-to-replace modules, consumers may be able to perform essential maintenance and service functions, thereby further reducing the need for an infrastructure of skilled service staff. Makers of copiers, computers, and many other kinds of electronics equipment are creating modular product architectures with self-diagnostic or over-the-wire diagnostic capabilities and easily replaceable modular components that are provided through local distribution channels or delivered to the customer's door. By reducing and simplifying service requirements, strategic partitioning of modular architectures into easily diagnosed and replaced components may free an organization's marketing process from the need for a skilled service infrastructure.

Decoupling technology and product development to achieve concurrent and distributed development of components. Just as product architectures can be decomposed into interacting functional components, the architecture of the processes an organization uses to develop, produce, distribute, and support its products can be decomposed into component activities that interact in specified ways.[8] Addressing a fundamental relationship between product and process architectures, Sanchez and Mahoney (1996) have argued that products design organizations, in the sense that the feasible organization designs for developing, producing, distributing, and servicing products are constrained by the product designs an organization adopts. As the following discussion explains, using a modular development strategy that standardizes component interface specifications at the beginning of component development processes creates new possibilities for organizing product creation and realization and brings several strategic benefits to the marketing process.

I first consider how fully specifying component interfaces at the beginning of component development processes requires decoupling technology development and product development,[9] which greatly improves the predictability of product creation processes. I then consider how the use of this modular development strategy allows for concurrent and distributed component development processes that may increase the efficiency of product creation processes, increase speed to market, and enable more extensive subcontracting for components. These benefits of a modular development strategy can simultaneously accelerate, extend the scope and reach, and improve control of the marketing process.

[8]The waves of business process reengineering and total quality management that recently have swept through businesses of all types have made many firms aware of the decomposability of their processes into well-defined activities and the need to specify how various activities contribute to and interact in creating value for customers.

[9]In this discussion, technology development refers to the process that develops new product and process components, whereas product development refers to the process that develops new product designs based on new and existing components.

Improving the predictability of product creation processes. To specify component interfaces fully at the beginning of component development processes requires the use of only those modular components whose functional behaviors and interactions with other components are well understood. Thus, the development of new modular components based on new technologies that are not yet well understood must not be undertaken in a modular product development process. Rather, development of new kinds of modular components is pursued off-line, in a technology development process that is parallel to but decoupled from product development processes (Sanchez and Mahoney 1996).

Intentionally decoupling technology and product development in this way removes most technological uncertainty from the process of creating new products and thereby substantially improves the predictability of the outcomes and timing of product development processes. Although intentionally separating technology and product development may raise concerns that technological innovation would be stymied, a discussion subsequently in this article argues that decoupling technology and product development makes both processes more efficient and enables faster and more frequent cycles in both technology and product development.

Increasing the efficiency of product creation and speed to market. As noted previously, an optimizing approach to product development typically results in a product design that is based on a complex system of integrated, tightly coupled component designs. In this approach, processes for developing tightly coupled components also become tightly coupled, because changing the design of one component generally precipitates a chain reaction of compensating changes in the designs of other components. GE Fanuc Automation, a leading maker of industrial automation systems, found that redesigns of components necessitated by changes in designs of other tightly coupled components consumed up to 80% of the development time and resources required to create optimized product designs (Sanchez and Collins 1998).

In contrast, a modular development strategy begins with a determination of the range of modular component variations required to provide an intended range of product variations and then defines the interfaces between components to accommodate the desired range of component variations. By fully specifying and standardizing component interfaces before component development begins, a modular approach to product development creates an information structure that defines the required outputs of all component development processes. As long as all component development groups create components that conform to the input and output specifications for a given modular product architecture, the processes of individual component development groups will be loosely coupled; that is, one group's development process will not be affected by the development processes of other groups. All component development processes then can be carried out concurrently (Sanchez and Mahoney 1996). When components can be developed through loosely coupled, concurrent development processes, reworking of component designs due to changes in other component designs is avoided, development resources for creating new products can be used much more efficiently, and speed to market can be accelerated greatly. Table 2 summarizes the key differences between optimizing and modular approaches to defining, designing, and developing product architectures.

Extending the reach of the marketing process. Managing development processes for tightly coupled components generally requires intensive communication and coordination among component development groups. Frequent management intervention also may be required to allocate costs and adjudicate disputes arising from component redesigns that are necessitated by design changes in tightly coupled components. Thus, developing product designs composed of tightly coupled components generally requires that development processes be tightly coupled and carried out within a single firm or group of closely linked firms (Sanchez 1996a; Sanchez and Mahoney 1996).

A modular design strategy that fully specifies and standardizes component interfaces before component development begins, however, fully defines the required outputs of component development processes and thereby facilitates expanded subcontracting for component development services. In effect, fully specifying and standardizing modular component interfaces enables an organization that is creating new products to shop for and coordinate component development services to be performed by the most capable component development firms. Using modular architectures as a framework for contracting with a global pool of component developers and suppliers enables a marketing organization to draw on the best available expertise to develop more and better component variations for leveraging a greater range of higher-quality product variations. Using modular architectures as a framework for subcontracting development of components also may reduce the initial investment, and thus the financial risk that a marketing organization must bear to develop new products, as well as the technical and managerial resources it must have to create new products. The reduced resource requirements of a modular development strategy therefore may enable an organization to sustain increased levels of product creation and create a broader range of products through its marketing process.

Loose coupling of component designs to create loosely coupled knowledge domains. Organizations that create products tend to develop technical knowledge structures that reflect the functional decomposition of components in their product architectures (Henderson and Clark 1990*). Thus, an organization that creates product designs based on complexly interrelated, tightly coupled components will tend to develop a knowledge architecture that reflects the complex structure of component relationships within its product architecture. The complexity inherent in a system of tightly coupled components, however, may limit the ability of an organization to distinguish clear cause-and-effect technical relationships within and among individual components in an architecture, which thereby limits the organization's ability to develop component- and architectural-level knowledge about the behavior and performance of its components and product architectures.

In contrast, a modular architecture creates loosely coupled knowledge domains focused on each loosely coupled component in the product architecture. The reduced complexity of component interactions in a modular architecture improves an organization's ability to discover cause-and-effect relationships among components and develop and evaluate new components. As a consequence, use of modular architectures may lead to greater efficiency and speed in technological learning, which stimulates and accelerates development of new components and architectures. In addition, when modular architectures are adopted as industry standards, technological

TABLE 2
Optimizing Versus Modular Processes for Product Definition, Design, and Development

	Definition	Design	Development
Optimizing Product Design	Consumer preferences are researched and aggregated to define the attributes of an optimal product. Optimal attributes are translated into required functions, features, and performance levels to be provided by product design.	Required product functionalities are decomposed into components, but some component designs are integrated during design optimization. Component interfaces are permitted to evolve during the design optimizing process.	Component designs evolve in an iterative optimizing process. Product architecture is defined by the final optimized product design. Thus, a product architecture is the output of the development process.
Modular Product Design	Marketing research determines the range of product attributes that will appeal to different kinds of consumers. Range of desired attributes is translated into range of functions, features, and performance levels to be leveraged from modular product architecture.	Modular product architecture is decomposed into discrete components. Interfaces among components are fully specified and standardized to allow a range of component variations to be substituted into product architecture.	Component development processes are carried out within the information structure of fully specified and standardized component interfaces and therefore may be concurrent, autonomous, and distributed. Product architecture defined in design stage does not change during development stage.

improvements achieved by any component developer may create substantial positive externalities for all firms that use the developer's improved components. I next consider how these effects of modular architectures on technological learning can accelerate the pace of technological innovation and market development in the marketing process.

Improving the efficiency and speed of technological learning. The inherent complexity of a system of tightly coupled components may limit an organization's ability to determine exactly what it knows about the component behaviors and interactions in its product designs—and therefore to begin to understand more clearly what it does not know about component behaviors and interactions. Use of product architectures based on complexly interrelated, tightly coupled components therefore may limit an organization's ability to identify specific opportunities for new learning about component behaviors and interactions that would improve the organization's product creation capabilities. The reduced complexity of modular architectures, however, provides an alternative framework for improved technological learning at both component and architectural levels.

Organizations that use the modular approach to product creation typically codify their understanding of component behaviors and interactions in "interface specification documents" (Sanchez and Collins 1998) and in component design protocols programmed into computer-aided design systems (Sanchez 1996b). These interface specifications and protocols represent design rules that inform designers what the organization currently understands about the behaviors and interactions of the components it uses and thus how those components can be used in modular architectures. By systematically defining modular design rules that embody what an organization currently knows about its components and their interactions, an organization that creates modular architectures can begin to discern more clearly the current limitations in its ability to describe and control component behaviors and interactions. Technological learning within the organization then can be focused more directly on achieving strategically important improvements in a firm's "ability to specify and control the performance characteristics" of its components and architectures (Venkatesan 1992, p. 103).

Some organizations that use modular design strategies also define the capabilities that make possible the various activities in their own and their suppliers' current process architectures. Definitions of current production process capabilities, for example, can be included in design rules to determine the new component variations an organization and its suppliers are currently capable of producing and assembling (Sanchez and Collins 1998). The limitations that a firm's distribution channels and service networks impose on the characteristics of a new product also may be defined and incorporated into design rules for specific components. By developing design rules that incorporate capabilities in an organization's process architecture, a firm can identify more readily opportunities for adding specific new process capabilities that would let the firm expand the scope or improve the efficiency of its product creation and realization activities.

Clearly defining an organization's process architecture also can facilitate the rapid dissemination of learning about specific process improvements throughout the organization. For example, AT&T has created a map of its process architectures that decomposes and categorizes the production activities carried out in its global network of factories. When learning in one factory leads to a process improvement in a given activity, an explanation of that improvement and the standard process category that it applies to are disseminated to all AT&T factories through its global information system. Each factory in the AT&T system then can identify readily the activity to which the new knowledge applies and quickly incorporate the process improvement in its own production system.

Stimulating development of new components. As long as all new component designs developed for a modular architecture conform to the interface specifications of the architecture, individual component developers are free to be innovate in creating new component designs. Coordinating component development processes by specifying only the input and output interfaces for components in a modular architecture therefore can encourage innovation in the development of better component designs.

Modular development processes also may stimulate improvements in key components by enabling closer involvement of key customers and suppliers in product creation. Because decisions affecting the design of a given modular component do not require extensive consultations with other component development groups but are constrained only by the interface specifications for that component, customer or supplier suggestions for improvements to specific components can be evaluated and acted on quickly and independently of other component development processes. Thus, it becomes easier for lead users (von Hippel 1988) to play a more active role in suggesting variations or improvements in designs of key components in new products. Boeing's modular design for the 777 aircraft, for example, facilitated the close involvement of lead customers such as United Airlines and British Airways in developing ideas for improving the 777's major components (Sanchez and Mahoney 1996). Modular development processes therefore may improve the ability of a firm to gather important market information from key customers and directly translate that information into better product designs.

Technology and market learning within industry-standard modular architectures. Modular product and process architectures are increasingly prevalent in rapidly developing technologies and markets (Dosi 1982; Sanchez and Mahoney 1996). One explanation for this observed association may be that the adoption of modular PPKAs in an industry creates substantial positive network externalities in technological learning. As firms in an industry join together to define industry-standard specifications for component interfaces, for example, the resulting loose coupling of component development processes within the industry often leads to more widely distributed, more efficient, and faster learning processes by those firms (Sanchez, in press). Thus, adopting industry-standard modular architectures appears to be an important mechanism for accelerating the development of an industry's collective technological capabilities (Dosi 1982; Langlois and Robertson 1992).

As more firms develop new and improved components within industry-standard modular architectures, they often create a growing array of component variations to serve specific application requirements and consumer preferences. Examples of this effect range from the proliferation of software programs and peripheral devices for the Wintel PC modular architecture to the increasing variety of seats, handlebars, gears, brakes, and other components available for the modular architectures of sports bicycles (Galvin 1998*). The availability of growing numbers of modular component variations compatible with an industry-standard product architecture makes it possible for marketing organizations to accelerate their exploration of market preferences by offering a growing number of modular component–based product variations.

Reducing costs and resource requirements for product creation. The foregoing discussions have described properties and strategic uses of modular PPKAs that, taken together, suggest several ways in which the use of modular architectures significantly change the economics of product creation, enabling firms to achieve greater product variety, faster technological improvement of products, greater speed to market with new products, and lower costs for creating new products. Although detailed comparative cost analyses are not currently available from companies that have adopted modular architectures, there are some broad measures that suggest the substantial impact that modular architectures can have on the technologically determined economics of product creation.

After adopting a platform approach to creating new cars that is similar to the modular development process previously described, for example, Chrysler Corporation reports that it develops new car platforms (from which Chrysler typically leverages several car models) in less than 30 months, using a platform development team of 700 to 900 people and for a total development cost of less than $1 billion. Using its previous traditional product development method, Chrysler typically took between 60 and 72 months to create a new car model, involved as many as 5000 people, and spent between $2 and $3 billion (Herlitz 1997*; Holmes 1995*). At GE Fanuc Automation, using a modular approach to create its industrial control products reduced both the development time and human resources required to create a new generation of products by 50% to 60% compared with the firm's prior traditional product development process (Sanchez and Collins 1998). These comparisons suggest that skillful use of modular architectures can reduce the costs of creating new products significantly, which thereby enables a firm to engage in heightened levels of product creation and improve the profit potential of its marketing process.

Implications of Modular PPKAs for the Marketing Process

The foregoing discussion has described some key properties and strategic uses of modular architectures. This section addresses the ways in which the strategic use of modular architectures can lead to significant changes in several aspects of the marketing process, both as it is represented currently in marketing theory and as it is carried out in professional practice.

I first consider the impact of modular architectures on marketing research, particularly with respect to segmenting markets and defining product attributes in modular product markets. I then consider how modularity changes marketing strategy, discussing both the need to define strategic roles for the components in a modular architecture and the potential to develop new approaches to positioning and branding modular products. Next, I examine the implications for market development processes of using real-time marketing research based on modular architectures to supplement conventional marketing research methods. I then describe the challenge to market development of managing a transition from producer- to consumer-controlled product differentiation, a transition that often occurs in the advanced stages of modular product markets. Then, I consider new approaches to supply chain and distribution channel design that suggest how modular architectures can be linked to new information technologies to create important new marketing flexibilities. Finally, I suggest ways in which the strategic roles assigned to components in a modular marketing process may influence the boundaries of the marketing organization.

These new aspects of the marketing process in modular product markets appear to rest on some fundamental assumptions that differ significantly from the assumptions underlying conventional marketing processes. Table 3 identifies and contrasts these underlying assumptions and the resulting differences in conventional versus modular marketing processes.

Marketing Research: Coordinating Market Segmentation and Modular Architectures

In a conventional marketing process, marketing research tries to discover various consumer preferences with respect to a product and to define market segments by aggregating consumer preferences into categories of preferences that are more or less shared among certain groups of consumers. Conventional marketing research then tries to determine the optimal set of product attributes that will appeal most strongly to the preferences that define a given market segment (Mahajan and Wind 1991). An evaluation process such as the product development funnel (Clark and Wheelwright 1993) then compares development costs with profit potential for various products and market segments. Single products or a limited number of product variations that appear to offer greatest profit potential are selected for development for targeted market segments. The implicit premise underlying this practice is that developing, producing, distributing, and supporting many product variations to serve the preferences of small groups of consumers or of individual consumers within market segments is prohibitively costly.

Modular architectures may make it possible, however, to leverage many different product variations to serve the specific preferences of small numbers of consumers or even of individual consumers within one or more market segments. The ability to leverage many product variations from modular architectures adds some new dimensions and

TABLE 3
Underlying Assumptions and Characteristics of Conventional Versus Modular Marketing Processes

Typical Characteristics of Conventional Marketing Process	Underlying Assumptions of Conventional Marketing Process	Underlying Assumptions of Modular Marketing Process	Resulting Characteristics of Modular Marketing Process
Marketing research is based on statistical analyses of samples that are small relative to target population and gathered only periodically.	Gathering preferences from each consumer in a target population is prohibitively costly; large-scale sampling is also costly.	Consumers' individual preferences for specific modular product variations can be gathered at low cost. Data on purchases of specific modular product variations can be gathered for entire populations in real time.	Individual consumers' preferences are gathered, often through interactive Internet, cable, and satellite connections. Changes in consumer preferences for product variations are analyzed continuously in real time for nearly entire populations of consumers.
Preferences of consumers must be gathered prospectively and aggregated to define optimal product attribute sets for a limited number of new product variations.	Product variations are costly to design and develop. Representative sets of consumer preferences therefore must be determined and development focused on creating products optimized to serve those preferences.	Consumers' perceptions of product variety and value are provided by variations in modular components. Product variations based on component variations can be leveraged from modular architectures at low incremental cost per product variation.	Real-time market research tries to determine full range of consumer preferences that might be served through modular product and process architectures. Marketing is involved in deciding flexibilities of modular architectures and strategic roles of modular components.
Emphasis is placed on defining a limited number of carefully differentiated products that can be produced and sold in large numbers.	Product variations are costly to produce; low production costs are realized through large-scale production of a limited number of product variations.	Large numbers of product variations can be produced by firms using flexible modular process architectures to coordinate component suppliers and service providers. Product variations based on component variations can be made for individual consumers at acceptable costs.	Emphasis is on offering large numbers of product variations, including mass-customized or personalized products.
Product variety may have to be limited to avoid imposing high inventory costs on distribution channels.	Extensive product variety is costly to distribute because large numbers of fully assembled product variations must be inventoried.	Modular product architectures make possible late point differentiation of products in distribution channels. Made-to-order product variations may also be delivered directly to individual consumers at acceptable cost.	Differentiating modular components are often added at a late point in distribution before delivery to consumers. Mass-customized or personalized products are often made to order and shipped directly to individual consumers.
Product variety may have to be limited to control service training requirements and spare parts inventory costs.	High levels of product variety cause high service costs because it is costly to stock many different kinds of spare parts, and service staff must be trained to maintain and repair many different components.	Service requirements can be simplified through use of self-diagnostic and/or easily replaceable modular components. Replacement components can be shipped directly to consumers by suppliers.	Service requirements are not considered as limiting product variety. Marketing emphasizes ease of maintenance and low-cost repair through simple replacements of modular components.
Extensive prospective market research is used to minimize risk of developing and introducing specific new product variations.	Producers must bear risk of defining, creating, and producing differentiated products targeted at identified market segments.	Producers can reduce product market risk by creating flexible modular architectures capable of providing large numbers of product variations and letting individual consumers decide what product variations they want (consumer-controlled differentiation).	Firms explore market preferences through use of real-time market research based on introduction of small lots of learning models leveraged from modular architectures. Personalized products leveraged from modular architectures may be made to consumer's order.

challenges to the process of segmenting markets and defining products to serve market segments. Most fundamentally, there is a need for marketing research that will be useful in *optimizing the flexibility* of modular architectures (Sanchez 1995a). In other words, rather than suggesting an optimal set of product attributes for each identified market segment, marketing research in a modular product market must help determine both the optimal number of modular architectures that should be created to serve the various consumer preferences in a product market and the optimal range of component-based functionalities, features, and performance levels that each modular architecture should be designed to accommodate.

Determining the optimal number of modular architectures for serving the various segments in a product market requires comparing the relative benefits and limitations of creating highly flexible modular architectures to serve consumer preferences in several market segments with the benefits and limitations of using more focused architectures to serve consumer preferences within a single market segment or a limited number of related market segments. New models and metrics are needed to represent the feasible trade-offs among (1) the financial benefits of increasing the flexibility and extending the market coverage of a modular architecture, (2) the costs of creating greater flexibility in a modular architecture, (3) the various technological constraints that could limit the flexibility and performance characteristics of modular architectures in a given product market, and (4) the relative performance of and likely consumer satisfaction with the product variations leveraged from more flexible versus more focused architectures.

Similarly, to determine the optimal range of component-based functionalities, features, and performance levels that a given modular architecture should be designed to accommodate, marketing research needs to develop insights into the marginal value of greater (component-based) product variety offered to a market segment. To develop such insights, consumer preferences for modular products must be described and analyzed in terms of the perceived value consumers in various market segments derive from each of the discrete functionalities, features, and performance levels that may be provided by modular components. Analysis of interdependencies in the values that consumers ascribe to each component-based function, feature, and performance level is also needed to determine the specific bundles of selected components that would appeal most strongly to different sets of consumer preferences.

More generally, marketing research in support of conventional product development can be characterized as working to identify the *means* in the distributions of consumer preferences that can be used to define aggregations of consumer preferences, so that individual product designs can be optimized to provide the product attributes preferred by consumers in specific market segments. Marketing research in support of modular products, however, must directly take into account the *variances* in the distributions of consumer preferences, so that modular architectures can be defined to serve the most profitable range of market segments and designed to provide the most profitable number of product variations within each segment. This new objective for marketing research in modular product markets invites marketers to work more closely with product designers to understand the technically feasible range of component variations (and thus product variations) that can be accommodated within a modular product architecture. In effect, market researchers and product designers must learn to work more closely together to develop a new understanding of how much modularity—and the resulting flexibility to leverage product variations—can and should be designed into modular product architectures.

Marketing Strategy: Defining and Managing Strategic Roles for Modular Components

Extending the objectives of marketing research to include defining modular architectures that can provide a range of component-based features, functionalities, and performance levels brings an important new dimension to the formulation and implementation of marketing strategy. In modular product markets, marketers must be able to define and manage the strategic roles that various modular components will play in creating perceived value in the product variations that are leveraged from a modular architecture[10] (Sanchez 1995b). They also must help define the common components that can be used most effectively in the various product models leveraged from a modular product architecture.

Defining strategic roles for components. The various components in a modular product architecture may be characterized as primarily performing one of four strategic roles: providing threshold, central, variety-enhancing, or plus-only product attributes in a modular product architecture (Bogner and Thomas 1996; Huang 1993).[11]

Threshold attributes are functions provided by components that are essential to the overall functioning of a product but are not perceived by consumers as adding value to the product as long as they function adequately. In essence, components that provide threshold attributes have the strategic role of simply functioning at a threshold level of acceptable performance and reliability. Failure to deliver the threshold level of performance and reliability in a market segment generally will result in a negative reaction by consumers, but increasing component performance and reliability beyond the threshold level will not increase the perceived value of the product. Examples of components delivering threshold attributes are the chassis, starter, and battery of a car and the bus and power supply of a PC. The strategic role of components determined by marketing research to provide threshold attributes is to be progressively reduced in cost through techniques such as value engineering while maintaining the threshold level of performance and reliability expected by customers in a given market segment.

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[10]This important extension of the marketing process may benefit from the use of tools such as the "house of quality" and other quality–function–deployment models for translating consumer-perceived product attributes into engineering design variables.

[11]Huang (1993) and Bogner and Thomas (1996) develop the concepts of threshold, central, and plus-only product attributes. This discussion introduces the fourth category of variety-enhancing product attributes.

Central attributes are perceived by consumers as central to a product concept, in the sense that increasing levels of performance by a central attribute will increase the perceived value of the product for most consumers in a market segment. An automobile's engine is a component that provides central attributes for most consumers, because increases in an engine's power and fuel efficiency, for example, generally result in an increase in the perceived value of an automobile for most consumers. Similarly, faster microprocessors, higher-resolution flatscreens, and longer-lasting and lighter batteries are improvements in central components that generally increase the perceived value of laptop computers for most consumers.[12] The strategic role generally assigned to components that provide central attributes is therefore continuous improvement in key performance parameters through the development of better component designs and technologies.

Variety-enhancing attributes are provided by components that are perceived by most consumers as sources of value-adding variety in a given product type but are not regarded as central attributes in distinguishing product variations. In many products, variety-enhancing components provide features (i.e., functions that are not central to a product concept) or styling variations that are used to distinguish models that are otherwise similar in the basic functions they provide. Component variations in the plastic case colors and shapes for "boom boxes" (portable audio systems), for example, provide value-adding variety for most consumers of those products, just as the introduction of new interior trim, convenience lights, and wheel styles is a valued source of perceived variety in new automobile models that are functionally identical to previous models. The strategic role for variety-enhancing components, therefore, is providing a changing array of featuring and styling variations needed to distinguish product models from other functionally similar similar models.

Plus-only attributes are derived from components that provide features that add value by delighting most consumers when they are present in a product but that, if absent, do not detract from the product's perceived value. Warning lights that indicate when a car's doors have not been closed completely or when a laptop computer is still running are examples of components that create plus-only value for most consumers. The strategic role for plus-only components is often selective probing of consumer reactions to novel functions and features not previously included in a product. In effect, introducing plus-only components provides a means to research latent consumer needs that could be served by a new kind of component within a familiar product architecture, thereby enabling discovery of new functionalities or features that can add to the perceived value of a product.

Managing the evolution of component-based attributes. Threshold, central, variety-enhancing, and plus-only attributes often follow certain patterns of evolution in a product market. Marketing research can play a key role in supporting the marketing process for modular products by identifying the pattern of evolution a specific component-based attribute is following and the timing of its transitions from one attribute stage to another.

Some components originally created to provide plus-only attributes may elicit a strongly positive evaluation by consumers that eventually leads to an increase in consumer expectations, and then, what originally was introduced as a plus-only attribute may evolve into a product attribute that consumers expect. When this evolution occurs, the attribute may become a means to create perceived variety in the product and, thus, may be regarded as a variety-enhancing attribute. For example, a light or sound that warns a driver that the lights of a car have been left on after shutting down the engine was a plus-only attribute in the 1970s but is now more or less expected by consumers in new car models. Car makers therefore have begun to offer a range of component-based variations of the feature, such as buzzers, bells, flashing lights, computer-based voices, and automatic switching off.

Similarly, a specific variation of a variety-enhancing component that elicits a strongly positive consumer response may take on the character of a central or threshold component. Emphasis in component development may then shift to identifying and providing the performance levels of that attribute demanded by various consumers. In the early 1990s, for example, Internet browsing was a variety-enhancing feature offered in some PCs, but by the mid-1990s, Internet browsing had become a central attribute of PCs for most consumers, with the consequence that the relative performance capabilities of Internet browser functions became an important basis of competition in the PC market.

Furthermore, when a central attribute in a product type achieves a certain level of performance, consumers may begin to adopt that performance level as a benchmark in judging such products, and the central attribute may, in effect, evolve into a threshold attribute. By the late 1990s, for example, high-performing Internet browsers effectively had become a threshold attribute in PCs for most consumers. High-performing Internet software must now be included in PCs, but further increases in performance levels currently seem to add little value in the eyes of most consumers.[13]

Evolutions of component-based attributes in a product market mean that the objectives of both marketing research and technology development must change as a product market evolves (Sanchez 1996b). Marketing researchers therefore must not only define the initial strategic roles for mod-

[12]The perceived value of a component that provides a central product attribute increases with the increasing performance of the component but often only up to some limit. Increases in an automobile engine's power greater than 300 horsepower, for example, are unlikely to elicit a corresponding increase in the perceived value of an automobile for most consumers. However, improvements in fuel efficiency (and corresponding reductions in operating costs) are likely to elicit increases in perceived value to a very high level before most consumers become indifferent to further increases.

[13]Often, central attributes will take on the character of threshold attributes when the technological development of the components providing the attributes reaches a plateau that limits the ability of developers to extract further performance increases from the technology. A technological breakthrough in component development that leads to a new round of performance increases, however, may cause a threshold attribute to revert to being a central attribute until performance gains reach the next technological plateau.

ular components in a marketing strategy, but also determine when consumer perceptions of the value added by each kind of component are shifting from one to another type of product attribute in this evolutionary process. Identifying such evolutionary shifts in component-based attributes is critical to revising marketing strategies effectively and to timely redeploying of technology and component development resources during the evolution of a product market.

Defining common components. Defining and designing modular product architectures with significant levels of component commonality across product variations can reduce component development and production costs substantially. Thus, an important task for marketing research in defining and developing new modular product architectures is to determine the performance characteristics of component designs that can be used in common across many product variations or perhaps even in several related product architectures. Two complementary methods—one drawn from marketing research and the other from modular design—can be used to define common components.

When consumers are familiar with a product concept and have developed preferences for the functions and performance levels they want a product to provide, conjoint analysis can be used to identify the component-based product attributes that are desired by all or most consumers and thus determine the most profitable grouping of components to be offered in all or most product models (Moore, Louviere, and Verma 1998*).

In the case of new product concepts for which consumers have not yet developed clear preferences or in product markets in which consumer preferences may change rapidly, however, the precision and reliability with which conjoint analysis can identify preferred sets of attributes and define common components may be limited. In such cases, the modular design technique of creating components with redundant functions may offer a technical solution to managing market uncertainty. In this approach, a common component design is created that can provide all the functions believed likely to be desired by the market at large. When a multifunctional common component is developed and subsequently used in a product variation intended to serve a specific set of preferences, only the functions that serve those preferences are activated in the component, whereas other functions designed into the component remain inactive (i.e., redundant) in that product variation. For example, many televisions use a common semiconductor that contains all the functions required in top-of-the-line, fully featured television models, but only certain combinations of functions designed into the semiconductor are activated when the semiconductor is installed in various low-end and midrange television models. As an increasing number of product functions migrate from mechanical to electronic to silicon to software implementations, the variable costs of providing components with redundant functions are decreasing rapidly, making the use of common components with redundant functions an increasingly viable approach to managing market uncertainties that may limit the use of conjoint analysis.

Marketing researchers in a modular product market therefore must work with design engineers to determine the technical and economic feasibility of creating common components with redundant functions. Such collaboration will be necessary to determine the extent to which the design technique of creating redundant functions can be used as a complementary or alternative approach to using conjoint analysis in defining common components.

Marketing Strategy: New Approaches to Market Positioning and Branding

Modular architectures make it possible to pursue marketing strategies that include new approaches to market positioning and building brand equity. Unlike "one-off" product designs, modular product architectures can be used to support a relational marketing strategy in which a firm positions itself as a provider of products that offer its customers several important benefits, including backward and forward compatibility, scalability, upgradability, modifiability, interconnectivity, and/or easy servicing.

Backward and forward compatibility of a firm's products can be provided to consumers by maintaining standardized component interfaces across successive generations of product architectures. For example, a firm could maintain standardized interfaces for connecting peripherals to successive generations of computers or attaching existing lenses to new camera bodies. Intergenerational compatibility also can be enhanced by ensuring that new generation architectures are compatible with any complementary goods consumers must invest in to use a product, such as cassette tapes, floppy disks, and so forth.

Modular architectures also can be designed to offer products that are scalable, that is, products whose capacity can be expanded by adding additional components (more memory cards, more stereo speakers, and so on). Modular products also can be made upgradable when designed to allow substitution of improved components for old components. Consumers also may be offered the ability to modify a product by mixing and matching component variations after purchase of the product, such as the Smart Car, jointly developed by Swatch and Mercedes, which allows consumers to change the exterior color of the car by attaching modular body panels of different colors. Interconnectivity can be provided in a product when an interface is designed into a modular product to enable it to be used in conjunction with another product. Philips's 29-inch Multimedia television, for example, contains a port for connecting PCs to the television and using its large screen for surfing the Internet. Easy servicing can be designed into modular products by locating parts that require servicing in an easy-to-replace module, as Canon did in designing its Personal Copier. By offering these postpurchase benefits of modularity to consumers, particularly in markets for durable and/or premium-priced goods, modular architectures can be used to create a platform for developing long-term customer relationships and increasing consumer satisfaction on the basis of these benefits.

The ability to use a single modular architecture to leverage many different product variations across a broad range of price points also calls for careful brand management of modular products, perhaps including the creation of distinct brands and differentiating functions and features for upmarket, midmarket, and downmarket products leveraged from a single modular architecture. In addition, because common components may be used to provide the central attributes in many different product variations, superior performance may not be available as a basis for differentiating products. In this case, variety-enhancing components that provide opportunities for featuring and styling are likely to play a primary role in brand strategies. In the market for portable audio products, for example, there is little difference in the main functional components used by most makers, so styling components such as plastic enclosures and control and display panels become primary sources of perceived difference in products. Thus, marketing strategy in some modular product markets may have relatively little interaction with central functional components and may become largely focused on managing variety-enhancing components as the primary means for building distinctive brands.

In some modular product markets, consumer familiarity with the functions provided by key components may create the potential for branding components, such as the nearly ubiquitous "Intel [microprocessor] inside" most PCs. For marketers of assembled products, the development of strong brands for components can be a two-edged sword. Creating a modular architecture that accommodates branded components enables an organization marketing an assembled product to leverage some of the brand equity of the branded components in promoting its own product. At the same time, because consumers' perceptions of the assembled product may be influenced significantly by their perceptions of the branded components in the assembled product, there is a possibility that the assembled product's brand equity will be diluted by or become largely dependent on the continued use of branded components, thereby creating a condition of strategic dependency on the suppliers of branded components. New research is needed to clarify the extent to which and the conditions under which branded modular components contribute to or detract from the building of durable brand equity for modular products.

Market Development: Incorporating Real-Time Market Research

Marketing research essentially aims to use relatively low-cost marketing research processes for identifying consumer preferences before committing to relatively high-cost processes for creating and realizing new products to serve those preferences. Conventional marketing research methods, however, sometimes are limited in the accuracy with which they can determine consumer preferences by the statistical limitations inherent in using small samples of a population. In addition, marketing research into new product concepts may be compromised when consumers are asked about their reactions to a potential product concept rather than an existing product with which they have prior experience or can interact directly (Mahajan and Wind 1991).

When a firm can use modular product and process architectures to leverage many new product variations at low incremental cost per variation, it may pursue a new set of possibilities for market testing and experimentation that can provide an important complement to conventional marketing research (Baldwin and Clark 1994; Sanchez 1995b). Recognizing this, some firms have begun to supplement conventional marketing research methods with real-time market research in which they leverage small lots of new modular product variations to research consumer preferences directly (Sanchez and Sudharshan 1993). Two new kinds of marketing environments are being used to conduct real-time market research, and each invites development of new kinds of marketing research methods for analyzing consumer reactions to new products.

Some firms have established new retailing environments in which they can observe consumer reactions to new modular product variations. As noted previously, Sony and Nike, through their company-owned retail outlets, Sony Shops and Nike Towns, gather real-time market information in trendsetting cities of the world by exposing consumers to a stream of new product variations. In addition to the real-time sales data gathered in these combined retailing and marketing research environments, these marketing settings offer new opportunities for observing and interpreting in situ consumer reactions to new product variations. This real-time marketing research environment therefore offers a new means to discover why different kinds of consumers will or will not buy different kinds of new product variations.

In researching consumer reactions in larger rollouts of modular product variations, electronic data integration (EDI) systems and bar-code readers in large retailers such as WalMart provide real-time data on the purchase decisions of nearly entire populations of consumers. The ability to expose populations of consumers to product variations that are based on carefully modulated variations in component-based functions, features, and performance levels makes possible a more precise, fine-grained analysis of consumer valuations of the product attributes provided by specific modular component variations. In addition, analysis of real-time data on repair and maintenance services provides further insights into the reliability of components and may help improve customer satisfaction by identifying components in need of improved designs. As growing use of EDI begins to link all stages of product creation and realization, real-time sales and service data increasingly may be used as "electronic kanban" that drive not just logistics and manufacturing, but also processes for defining and creating new modular components and architectures (Sanchez 1996a).

The growing availability of large sets of real-time sales and service data, coupled with the flexibility to leverage new product variations from modular architectures at reduced cost, challenges marketing research to develop new methods of market analysis. In particular, there is a need to supplement current statistical techniques for determining central tendencies in *static* data sets with new mathematical methods (such as topological analysis) for discovering divergences in *dynamic* data sets that can yield new insights into evolving consumer preferences and newly forming market segments.

Market Development: Managing a Transition to Consumer-Controlled Product Differentiation

Just as flexible manufacturing systems ushered in a new era of production flexibility in which the economic order quantity for some firms became a single product, the flexibilities of modular product and process architectures are making it possible to configure a mass-customized product based on a combination of modular components selected by an individual consumer. Perhaps the most profound change in the marketing process occurs when the flexible configurability of modular architectures effectively allows the locus of product differentiation decisions to shift from producers to consumers (Sanchez and Collins 1998).

The transition from producer- to consumer-controlled product differentiation often follows an evolutionary path that parallels the development and use of modular architectures in an industry. When first adopting a modular approach to product design, firms often develop proprietary modular product architectures with functional decompositions and interface specifications unique to each firm. Adopting a modular architecture used by several (or perhaps all) firms in an industry, however, can create several positive network externalities that might induce at least some firms to adopt an open-system or industry-standard modular product architecture based on standardized components and interface specifications. When complementary goods (such as computer disks or batteries) are standardized across many or all firms, for example, the large-scale production and distribution of industry-standard goods lowers costs and increases convenience for consumers. Similarly, when employees in an industry develop common expertise in developing, using, and maintaining products and processes that conform to an industry-standard architecture, the common experience of employees within an industry creates a pool of human skills that all firms using the architecture can access. In addition to these supply-side positive externalities of open architectures, there are demand-side pressures from corporate and individual consumers who are wary of purchasing products that are based on proprietary product architectures that would make them dependent on a single manufacturer for product upgrades, complementary goods and supplies, and technical support.

As a standard architecture is adopted in an industry and becomes widely used, sophisticated consumers may develop sufficient understanding of the functionalities provided by various components in the architecture to select the component variations that provide the specific functionalities and performance levels they prefer to have in the product. In this case, knowledgeable customers may prefer to select their own bundles of component-based functions, features, and performance levels, rather than leave it to producers to choose which component variations to bundle together. Eventually, some firms will recognize that allowing consumers to select their own preferred combinations of components within a modular architecture can be the basis for a new marketing strategy that supports a shift to consumer-controlled product differentiation. Currently, producers in consumer markets as diverse as consumer electronics, pagers, trail bikes, PCs, banking services, and power tools have "opened" their product architectures to allow knowledgeable consumers to configure their own preferred combinations of functions and components. Consumers who are not knowledgeable about the functional components in a modular architecture still can assume at least some control of product differentiation by using knowledgeable third parties (value-added vendors or retailers) to help them select appropriate combinations of components.

When components used in industry-standard modular architectures are produced in large numbers and achieve low unit costs through economies of scale, the prices of mass-customized, consumer-differentiated modular products may become comparable to the price levels of producer-differentiated product variations. When this occurs, few consumers may be willing to compensate producers for carrying out traditional marketing processes for defining, developing, and marketing specific product variations. In such cases, the focus of the marketing process must shift fundamentally from defining the attributes for specific producer-differentiated products to defining flexible modular architectures for leveraging product variations to be configured by individual consumers. Informing consumers of the available variations in components and establishing new communication channels for receiving consumer choices of component variations then become central activities in developing a market for consumer-differentiated products.

Traditional retail channels may be used to gather information on the specific modular product variations desired by individual consumers and to deliver these products to consumers, but increasingly, the marketing process for mass-customized modular products is using more direct, interactive ways of communicating with consumers. There is growing use of the Internet as a low-cost communication link between consumers and producers of modular products, though mail, toll-free telephone calls, and fax also offer more conventional means of communicating directly with individual consumers. For many consumer-differentiated modular products, door-to-door distribution by express delivery services such as Federal Express has become the cost- and time-effective norm. Thus, developing a market for consumer-differentiated modular products generally brings a marketing organization into more direct contact with its customers and requires a marketing process with systems capable of managing large numbers of individual customer relationships.

Finally, a shift to consumer-controlled differentiation in a product market invites new product strategies that focus on achieving rapid innovation and improvement in the key components that influence consumers' purchase decisions most. Sun Microsystems, for example, focuses on development of its Sparc microprocessor and programming languages for Internet applications, both of which provide key functionalities to customers of Sun's customer-differentiated workstations and servers. In addition, when the ability of producers to use products per se to differentiate their product offers diminishes, nonproduct aspects of the product offer, such as maintaining high service levels and developing effective customer management systems, become increasingly important.

Supply Chain and Distribution Channel Design: Creating Greater Marketing Flexibility

In contrast to the emphasis in conventional marketing processes on designing optimal distribution channels to support a specific line of products targeted at a well-defined market segment, a key objective of channel design in modular product markets is creating flexibilities in supply and distribution channels to support the creation and delivery of many different product variations to many different kinds of consumers.

Information technologies increasingly are providing standardized communication interfaces, data structures, and procedural protocols (such as EDI) that create modular information-processing architectures that link firms electronically with their supply and distribution channels. Using standardized information architectures to achieve the flexibility of quick connectivity (Sanchez 1996b) and interoperability (Hald and Konsynski 1993) among firms requires standardizing the descriptions of the parts, products, and services being coordinated through the information architecture. The decomposition of modular product and process architectures into well-defined, clearly identified components and activities therefore helps support the formation of "electronic hierarchies" for coordinating firms in electronically mediated supply chains (Malone, Yates, and Benjamin 1987).

More generally, the use of standardized information architectures makes possible new kinds of "virtual value chains" (Benjamin and Wigand 1995) in global networks of firms engaged in creating, producing, distributing, and servicing large numbers of modular product variations.[14] The Swedish furniture firm IKEA, for example, uses a global information system to coordinate the design, production, and logistics activities of a global network of more than 1800 suppliers of modular furniture components. The combined use of modular architectures and global information systems extends the reach of IKEA's product creation and realization activities to more than 50 countries (Normann and Ramirez 1993). It also enables the firm to schedule concurrent and globally distributed processes for developing and producing modular components and to shift production of modular components among various suppliers and regions in response to changes in regional demand, exchange rates, and other factors.

Thus, in marketing processes for modular products, effective use of standardized information systems may enable a marketing organization to attain new levels of concurrency and speed, a more global reach, and greater configurability in both its supply chain and distribution channel designs.

Marketing's Expanded Role in Shaping the Boundaries of the Firm

When a modular component is considered to provide a threshold attribute and therefore is given the strategic role of progressive cost reductions, global outsourcing may be the best way to obtain the component at lowest cost. A cost-driven outsourcing strategy therefore might place the development and production of threshold components outside the boundaries of the firm. In contrast, given the key contribution of central attributes to the perceived value of a product and the strategic role of central components to achieve higher performance levels, development and production of central components is likely to be considered a core capability that a firm will internalize or share only with close strategic partners. To carry out the strategic role of creating new variety-enhancing components, a firm may seek to source component variations from a large, possibly global network of component developers and suppliers with diverse development and production capabilities. To probe latent market preferences selectively by introducing plus-only components, a firm may seek to establish working relationships with specialist firms outside its industry to obtain new kinds of components capable of providing new kinds of functionalities and features.

Thus, as strategic roles for modular components are defined in a marketing process, the strategic roles assigned to modular components will have a significant impact on whether internal or external resources are used to support the marketing process. Marketing's mission to define and manage the strategic roles of the modular components in a product architecture therefore gives the marketing process an expanded role in shaping the boundaries of the marketing organization.

Conclusion: Toward a New Marketing Process for Modular Product Markets

This discussion has described several properties and strategic uses of modular architectures that suggest the emergence of a new approach to product creation with important implications for the future evolution of the marketing process. I conclude this discussion by summarizing some of the most important changes that modular architectures are bringing to the marketing process and suggesting some of the related issues that the marketing process must address as a product market "goes modular."

A shift from creating products to creating platforms. Product creation in many product markets is undergoing a transformation from creating products to creating modular architectures that serve as flexible platforms for leveraging product variety and change. There is clearly potential, however, for consumers to be confused if they are offered too many product variations. Moreover, using modular architectures as platforms for rapid technological upgrading of products may increase consumer hesitation to buy current product models when they anticipate that improved models are likely to be introduced in the near future. These potential reactions of consumers suggest that there are diminishing marginal returns to increasing product variety and elevating rates of product change. The transformation from creating products to creating platforms therefore challenges the marketing process to develop new models and methods for determining how much product variety and change is most advantageous to design into modular architectures.

Extending the objectives of market segmentation. The flexibilities of modular architectures make it possible to leverage a wider range of product variations to serve the preferences of more finely segmented markets and even to

[14]The progress of the International Standards Organization (ISO) in establishing, disseminating, and certifying various ISO 9000 standards for quality assurance processes and specific production process capabilities is defining, in effect, architecture of standardized process capabilities that will facilitate the electronic configuration of globally dispersed capability providers into virtual value chains for modular product creation and realization.

mass-customize products for individual consumers. Inevitably, however, there are technological limitations on the flexibility that can be created in an architecture. Market segmentation therefore remains an important objective of the marketing process, because the flexibility designed into a modular architecture will need to be focused on serving some bounded range of consumer preferences in a market. To define the range of preferences a modular architecture should be designed to serve, however, market segmentation must become as adept at identifying the variance in the distribution of consumer preferences within a market segment as it is at defining the preferences at the mean in that distribution.

Growing use of flexible architectures to manage market uncertainty. When future consumer preferences are uncertain, the flexibility to accommodate a range of product variations may be designed into a modular architecture as a means for managing the irreducible uncertainties as to which product variations consumers will want in the future. Because consumer preferences generally are unformed and, thus, especially uncertain when new product concepts are brought to market, modular architectures can offer a flexible vehicle for a more interactive "sensemaking" exploration of a new product concept by producers and consumers (Rosa et al. 1999*). In effect, flexible modular architectures offer a new technological means for the marketing process to become more proactive in shaping consumer perceptions and defining the dimensions of the product space that a new product concept eventually will occupy. Thus, modular architectures offer new possibilities for the marketing process to devise marketing strategies that are both driven by evolving consumer preferences (Day 1990) and more capable of driving the formation of consumer preferences in a new product market.

Closer integration of marketing with other functions. A broad range of strategic flexibilities can be designed into a modular product architecture. Deriving the full strategic benefits obtainable from flexible modular architectures, however, requires extensive coordination of the marketing objectives for the architecture with the engineering design, manufacturing processes, and logistics systems needed to create and use the flexibilities in that architecture. In converting to modular architectures, many organizations may find that existing marketing processes focused on defining and developing single products do not address the full scope and depth of the engineering, manufacturing, and logistics concerns that must be coordinated to define, create, and use modular architectures to greatest effect. Thus, for many firms, adopting a marketing process based on modular architectures will require devising new planning and development processes that are capable of integrating a broader set of functional activities in greater detail than they previously have undertaken in the marketing process.

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