Chapter 27

Industry Standards, Modular Architectures, and Common Components: Strategic Incentives for Technological Cooperation

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Interfirm cooperation in defining industry standards has played a critical role in underpinning the technical development of industries for several decades. Recent years, however, have witnessed both expansions of voluntary standards setting activities and extensions of interfirm cooperation in adopting *standard modular architectures* and *standard modular components* used in those architectures. This recent deepening of technological cooperation is now playing an increasingly critical role in global processes for creating new products and managing value chains in many industries.

This paper reviews the key role of "upstream" industry standards in establishing enabling technologies, defines the concept of modular architectures, and identifies strategic incentives that exists today for extended forms of technological cooperation by firms in adopting standard modular product architectures. We first identify several demand-side incentives for adoption of modular architectures that result from increasing global demand for better differentiated and higher performing products at competitive prices. We then discuss supply-side incentives for interfirm cooperation in adopting standard modular architectures and common components that enable firms to achieve *quick connectivity* and *interoperability* with other firms in eBusiness processes for assembling virtual value chains. We conclude with some observations on how the transition from use of "closed-system" proprietary architectures to adoption of "open-system"

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standard modular architectures requires new cooperative strategies for both product market and supply chain management.

Introduction

The mainstream of strategic management theory has typically focused on competitive interactions between firms in marketing products, assembling value chains that confer favorable positions in an industry structure, and attracting superior inputs from resource markets. Nevertheless, cooperation among otherwise competing firms occurs in many forms and is a common, important, and often essential strategic management concern (Sanchez, Heene & Thomas, 1996). As this paper will suggest, interfirm *technological cooperation* increasingly plays a central role in the emergence and development of new product markets and new industries.

The discussion in this paper is based on the following working definition of technological cooperation:

> *Technological cooperation* is the voluntary coordination across firm boundaries of technology choices, design decisions, and technical specifications.

"Voluntary" in the above definition means that cooperation is not mandated by a government authority and furthermore that decision makers in cooperating firms believe that at least some alternatives to cooperation actually exist, even though they may be "second best" and not as attractive as cooperating. "Coordination" means the creation, acceptance, and management of acknowledged interdependencies in the decision making of two or more firms. The discussion in this paper explores a number of ways that interfirm coordination can occur in choosing technologies, deciding about product and process designs, and adopting technical specifications for products and processes.

A fundamentally important form of technological cooperation centers on the creation of a *common technical infrastructure* that is adopted by all or most firms in a new industry and that enables development of a new industry's products and processes. Enabling technologies that are used in common by firms in an industry, however, tend to become part of the "background" of an industry and quite often escape the attention of management researchers. One objective of this paper is to bring to the fore the fundamental importance of such enabling technologies in an industry — and thus to draw attention to the strategic importance of interfirm cooperative initiatives that give rise to an industry's enabling technologies in various forms.

A further objective is to clarify the growing strategic importance in establishing enabling technologies today of interfirm cooperation that leads to the definition and adoption of *standard modular product architectures* and *standard modular components* that result in use of *common components* by many or all firms in an industry. Using product architectures as focus of investigation illuminates several forms of technological cooperation within an industry that have not been widely recognized previously in cooperative strategies research. Broadly speaking, the primary focus of cooperative strategies research to date has been "horizontal" cooperation between firms at the same stage of an industry structure and "vertical" cooperation between a firm and its key suppliers or between a firm and its key customers, as suggested in Figure 27.1(a). An architectural perspective on development of new technology and products, however, helps to identify a number of other horizontal and vertical interactions between participants in an industry that are equally important as forms of strategic cooperation, as suggested in Figure 27.1(b). The architectural perspective developed in this paper therefore suggests an expanded typology of technological cooperative interactions that should be investigated in future research into cooperative strategies.

This paper begins by summarizing some essential — but inadequately researched — forms of technological cooperation in setting *industry standards* that have historically been important in establishing new enabling technologies, such as cooperative agreements to adopt standard terms, measures, and performance tests that facilitate sustained technology development. We also examine the ways in which voluntary adoption of standard materials, product specifications, and performance classifications both create significant positive externalities and limit negative externalities for cooperating firms in a new industry.

We then examine the nature of modular architectures and common components, and consider both demand-side and supply-side incentives in the "global economy" for adoption of modular architectures. We first consider supply-side incentives that encourage individual firms to adopt modular product architectures, and then consider demand-side incentives for extended technological cooperation among firms in adopting standard modular architectures and common components. Demand-side incentives for adoption of modular architectures include growing market demand for a greater variety of more technically sophisticated products, including products that give consumers the benefits of *scalability, upgradeability, extensibility, and connectivity.* On the supply side, the ongoing globalization of industries is creating increasing rewards for firms that can achieve *quick connectivity* (Sanchez, 1996) and *interoperability* (Hald & Kosynski, 1993) with other firms in configuring virtual value chains, and we consider the essential role of standard modular architectures and common components in enabling new levels of global interoperability and quick connectivity.

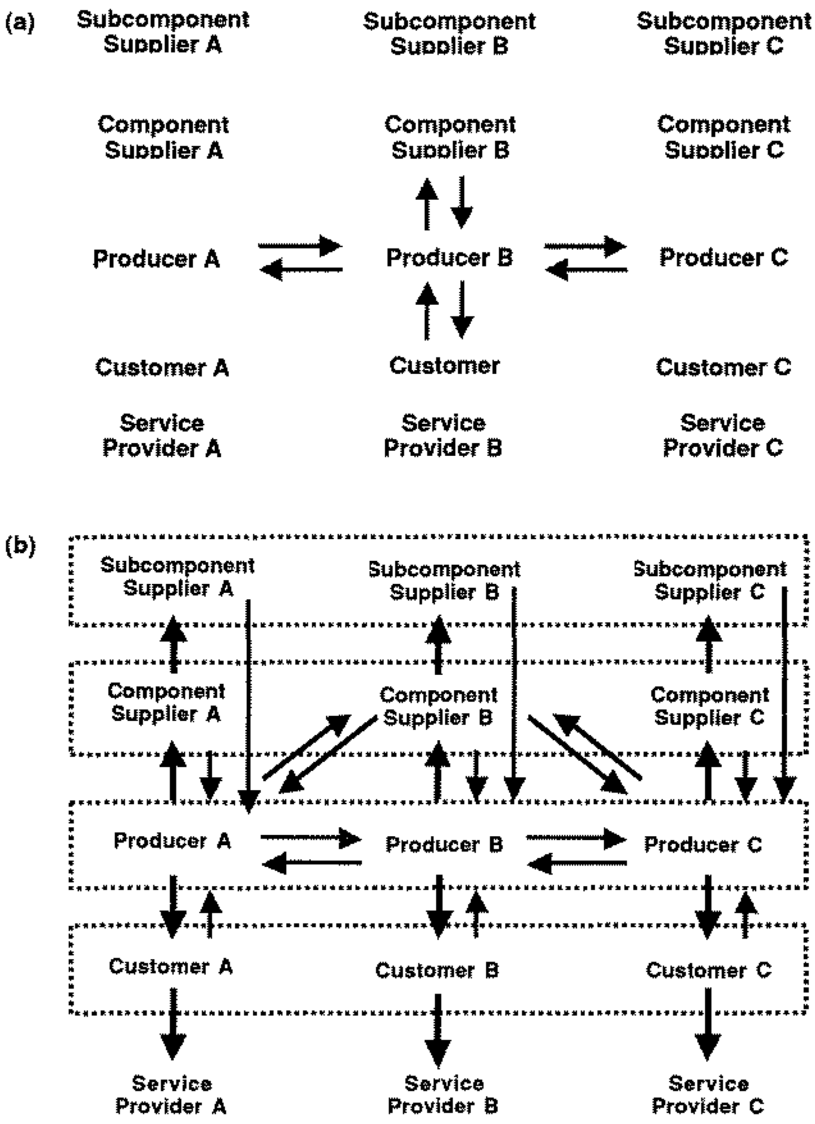

Figure 27.1: (a) Usual focus on interfirm interactions in cooperative strategies research; (b) New cooperative interactions brought into focus by architectural perspective.

We also consider how emerging eBusiness processes based on Internet-based interoperability and quick connectivity are further strengthening incentives for modular cooperation among firms.

The concluding sections explain some key ways in which the evolution from "closed-system" proprietary architectures to "open-system" modular architectures requires new forms of cooperative strategies.

The Role of Industry Standards in Creating Enabling Technologies

The emergence and growth of a product market depends on the development of a core of technologies that enables the creation and realization of new and improved products and processes. The development of enabling technologies for a new industry, in turn, depends on the establishment of a standard technical language and standard technical measures and tests that are understood and used by all participants in the industry, including firms that develop, produce, and market products, their suppliers, and quite often their customers as well. In effect, to become useful, a potential enabling technology must be developed into a common technical infrastructure that is understood and used by all the firms and individuals that participate in an industry. Long-term commercial development of a product market also depends importantly on the adoption by participants in the product market of standard material specifications, product specifications, and performance classifications. This second wave of standardization is vital in creating positive network externalities that benefit all firms in a product market and limit potential negative externalities that could harm those firms. We briefly consider some examples of each of these critical standardization activities and the forms of interfirm cooperation that commonly give rise to such standards.

Standard Technical Language, Measures, and Tests

Before people can begin to work together in the many ways needed to develop a new technology, they must be able to communicate with each other about the *underlying physical phenomena* that need to be managed in the technology, the *uses* to which the technology will be applied, and the degree of *control* achieved in applying the technology to specific purposes. Communicating about each of these aspects of a new technology requires the creation of an infrastructure of standard technical language, measures, and tests that are understood by all participants in the technology development process.

Consider, for example, the "display technology" that enables products like the familiar tube-based computer monitor or television. Developers of the technology that enables such products must have a standard technical vocabulary for describing the various physical phenomena involved when beams of electrons are emitted within the glass tube, strike a light-emitting coating on the front of the tube, and produce an emission of visible light. Moreover, the intended use of this technology to create images that will be viewed by humans requires the elaboration and precise definition of that specific context of use of the technology — e.g., the range and mix of colors, light intensity, and image resolution that must be produced to be easily perceived by humans under various use conditions for the product. Each of these aspects of the application of the technology must then be measured in some way, and this requires the creation of standard units of measure for representing color composition (wavelengths of light present), light intensity (lumens), and image resolution (pixel count). Further, standard performance tests are needed to assure that various firms and people in an industry use these standard measures in a consistent way in describing the degree of control (i.e., predictability and consistency) achieved in using the technology to create visual images. For example, light intensity must be measured at a standard distance from the source of the light to develop measures of luminosity that are comparable across various products and contexts of use.

The creation of a common technical infrastructure of standard technical language, measures, and tests often begins in the early research into a new technology undertaken in university or government laboratories. Although large companies may conduct their own research in their own laboratories, the growing complexities and costs involved in developing emerging technologies today frequently create incentives for companies to cooperate in jointly funding basic "pre-competitive" research into such technologies, either through research alliances or new industry associations formed to explore the potential of a new technology. The output of such research is typically a set of standard technical terms, measures, and tests for describing and investigating the technology. Cooperating firms in an industry can then benefit from the formation of a pool of technical people who understand the standard terms, measures, and tests and can apply them in the further development of the technology.

Standard Material Specifications, Product Specifications, and Performance Classifications

The commercial development of a product market based on a new enabling technology is often stimulated by interfirm cooperation in the adoption of standard material specifications, product specifications, and performance classifications. The incentives for firms to cooperate in this second wave of standardization include the creation of significant positive network externalities that can benefit all firms in a product market and the limitation of potential negative externalities that could harm firms.

The creation of standard specifications for the materials that will be inputs to a new industry facilitates the formation of upstream suppliers, because adoption of standard material specifications removes the technical uncertainty about what suppliers will have to provide to the new industry and signals that there is likely to be a growing base of demand for materials made to those specifications. Similar incentives are created for suppliers of process machinery for the new industry, who can then design machines that are capable of reliably processing materials that conform to the standard specifications. Downstream suppliers of maintenance, repair, and other support services can also benefit from knowing what kinds of processes they will have to develop to work with the standard materials they will encounter in the new products. Firms interested in participating in an emerging industry therefore have significant incentives to cooperate in setting industry standards for materials as a way of reducing the technical and commercial uncertainty associated with the emerging industry and thereby attracting an adequate base of suppliers of essential inputs.

An example may help to illustrate these effects of and incentives for cooperation. In the early days of the automobile industry in the US, there were more than 100 small-scale automobile manufacturers, each of which manufactured its own unique fasteners (primarily screws and bolts) used in assembling its vehicles. None of the car makers had sufficient volume to attract the interest of efficient, large-scale screw and bolt suppliers. In addition, the rise of a maintenance and repair industry for servicing automobiles was frustrated by the fact that a unique set of screwdrivers, wrenches, and other tools had to be used to work on the automobiles made by each of the more than 100 producers. Recognizing the high opportunity cost of using idiosyncratic sets of fasteners within each company — and the lack of any compensating advantage to be obtained from the use of idiosyncratic fasteners — a number of automobile producers joined together to agree on standard specifications for a range of screws and bolts that would be used by all the cooperating firms. This cooperative standards setting created a significant market for standard fasteners, attracted supply of those fasteners by large-scale fastener producers, and thereby lowered costs for fasteners for all firms using the standard fasteners. Subsequently tool sets could also be standardized, which stimulated the growth of a service infrastructure of automobile repair businesses by lowering required investments in tools. The benefits realized through the standardization of fasteners soon led to further initiatives to standardize lubricants, fuels, and other common inputs in the automobile industry and encouraged the founding of the Society of Automotive Engineers (SAE) to develop standard material specifications and related measures and tests.

Interfirm cooperation in establishing standard product specifications and performance classifications has also played an important role in the development of new product markets. When consumers are unfamiliar with new product types or are otherwise unable to judge the quality and performance offered by products from different producers, industry standards for describing various types and performance levels of products help to reduce consumer uncertainty about a product, reduce concern about buying a new product for the first time, and facilitate comparisons of competing products. The establishment of standard product specifications and performance classifications have greatly assisted the development of markets for products as diverse as steel, hard-disk drives, engineered wood products, automobile tires, computer monitors, fasteners, electric motors, and pumps.

Standard product specifications and performance classifications can create significant positive network externalities for firms that cooperate in adopting those standards. As more firms adopt such voluntary standards, users of those products learn how to assess the quality and performance of the products offered by the cooperating firms, and growing consumer confidence in specifying and using products that meet those standards benefits all cooperating firms. Similarly, the existence of product standards and classifications helps to limit negative externalities that could result if non-standard products fail to perform adequately in use, or if use of an inappropriate grade of product leads to a failure. When customers understand that standards do exist to assure that a given type of product will perform reliably, that understanding can limit the damage that might otherwise be done to the reputation of a product type when non-standard or inappropriate grades of products fail in use.

Modular Architectures and Common Components

Technological cooperation among firms is now going beyond adoption of standard terms, measures, tests, materials, and product classifications and increasingly extends into the very structure of the products the firms in an industry produce. In this section we introduce the concepts of *product and process architectures* and the *components* that make up those architectures. We also consider the special properties of *modular architectures*. In subsequent sections we investigate some key incentives in the global economy for firms to cooperate in adopting standard *modular product and process architectures* and *common components* in their modular architectures.

An *architecture* is created when (a) the design of a product or process is decomposed into functional components and (b) the ways in which the components will interact in the design are determined and specified (Sanchez, 2001).

Decomposition partitions a design into *functional components* that will work together to create the overall functionalities desired from the design. Assembled products like personal computers have the most visible and familiar decompositions into functional components (typically a microprocessor, memory card, hard disk, monitor, keyboard, and so on), but designs of services and other processes are also decomposable into specific activities or "process components." The vertical set of blocks in Figure 27.2 represents the decomposition of a *product architecture* into functional components, while the L-shaped array

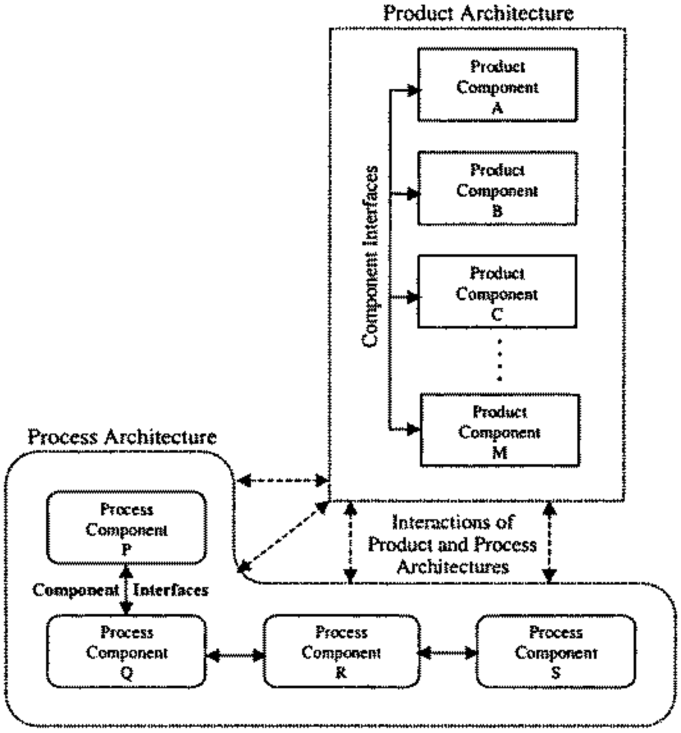

Figure 27.2: Functional components and interfaces in product and process architectures (adapted from Sanchez, 2001).

of blocks represents the decomposition of a *process architecture* — for example, the overall process for creating and realizing the product — into specific activities.

The ways that the functional components of a product or process architecture must interact to work well together is defined by the *component interface specifications* for a design. Interface specifications (Sanchez, 1999) define

- the way one component physically connects to another
- the spatial position one component will occupy relative to other components
- the way in which the output of one component is transferred to another component
- the way in which one component communicates with and controls or is controlled by another component
- other ways in which the functioning of one component may affect the functioning of another component in the architecture.

In effect, component interfaces define and control the way the functional components in a product or process architecture fit and work together *as a system.* Component interfaces are indicated in Figure 27.1 by the solid arrows between the functional components of the product architecture and the process architecture.

Creating a product or process architecture requires knowledge about (a) how the overall functionalities desired from a product can be decomposed into specific functional components and (b) how those components will have to interact to work well together in the architecture. Moreover, technical knowledge in an organization usually becomes clustered around the design, development, and improvement of the specific types of components that the firm uses in its product and process architectures. Thus, the way a firm decomposes its product and process architectures into components largely determines the specific technical knowledge the firm will need and is likely to develop in creating new products and processes.

Modular architectures are architectures in which component interfaces have been specified to allow the "substitution" of a range of component variations into the architecture without having to change the designs of other functional components in the architecture (Garud & Kumaraswamy, 1993). This flexibility of the interfaces in a modular architecture allows the "mixing and matching" of different "plug and play" component variations within an architecture to configure specific product variations (Sanchez, 1995a, b; Sanderson & Uzumeri, 1997). The substitutability of a range of component variations within modular product and process architectures is suggested in Figure 27.3.

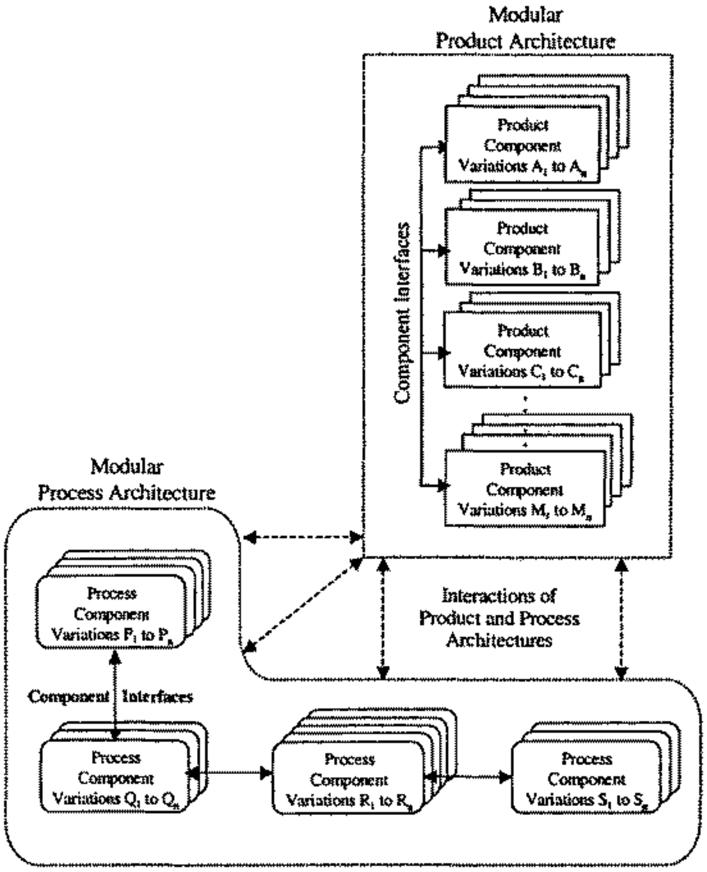

Figure 27.3: Functional components and interfaces in modular product and process architectures (adapted from Sanchez, 2001).

Perhaps the most familiar example of a modular product architecture is the personal computer, which makes possible the ready configuration of many different personal computer models from various combinations of microprocessors, memory cards, hard disks, and other components. Analogously, a modular process architecture is one that allows the mixing and matching of a number of process component variations within the same process architecture. For example, various kinds of development, production, distribution, and support activities may be performed by a firm's own functional groups or provided by external suppliers, but all activities can "plug and play" within the same process architecture.

The adoption of modular product and process architectures can bring a firm significant *strategic flexibilities*. Product component variations can be mixed and matched to configure many product variations to serve many market segments and customer preferences. Modular product architectures can also support rapid upgrading of product performance by "designing in" upgradeability of key components as technologically improved components become available. Creating modular process architectures helps a firm to outsource value-adding activities and to reconfigure its supply chain for developing, producing, and supporting products to meet a changing and diverse array of market demands (Sanchez, 1995a, 1995b, 1996, 1999).

When the component interface specifications in a firm's product and process architectures constrain the firm to use only specific components, the inflexibility of those component interfaces will impose *strategic inflexibilities* on the firm. For example, a product component interface that requires use of a specific component design will limit the firm's ability to provide a product that meets varying customer needs for the function provided by that component. Dependence on a single component design may also create a strategic dependence on a single supplier for that component. Similarly, an inflexible process component interface that locks a firm into using only internal processes to perform some activity can prevent the firm from using an external supplier to provide that activity. In effect, inflexibilities in a firm's current product and process component interfaces constitute "capability bottlenecks" that limit a firm's strategic flexibility to respond to demands for variety and change in its products and processes (Sanchez & Collins, 2001).

As we discuss further below, a firm may obtain a number of strategic benefits when it cooperates with other firms in an industry to define and adopt a standard way of decomposing product and process architectures into functional components and a set of standard modular specifications for the component interfaces in those architectures. To clarify the origins of those strategic benefits, we next consider some key characteristics of contemporary competitive environments that are creating new incentives for interfirm cooperation in adopting standard modular architectures and common components.

Contemporary Competitive Environments

Business environments are increasingly characterized by globalization, interconnectivity among products, and rising customer sophistication. These trends are creating both new competitive demands and new opportunities for interfirm cooperation in adopting standard product architectures and components.

Globalization means that more consumers around the world are achieving disposable incomes that enable them to become customers for a growing array of high value-added goods and services like automobiles, electronic products, telecoms devices, fashion, financial services, and other high value-added products. As a result, more and more product markets are becoming global in scope, having reached a critical mass of national and regional consumer demand adequate to invite active competition by both domestic and international companies. At the same time, globalization also means that more and more competitors are becoming capable of offering attractive products to global markets.[1] The joint effect of demand-side and supply-side globalization is heightened product market competition — but also increasing rewards to those firms that can offer the most competitive products to markets globally.

Interconnectivity means that more and more consumers and firms are becoming connected by various forms of inexpensive communication channels, especially of course the Internet. As more consumers become connected to the Internet, they have greater ability to investigate products and shop for the most attractive product offers available nationally or globally, thereby bringing much greater transparency to product markets and higher levels of consumer awareness about the relative merits and prices of alternative products.[2] At the same time, firms are increasingly communicating through the Internet with a global pool of "wired" suppliers to search for the best value in outsourced components and services for their product creation and realization processes, bringing transparency and global access to supplier markets as well. As the costs of global logistics continue to fall in relation to the value of goods being shipped, more and more firms are learning to assemble and manage Internet-mediated "virtual value chains" that link suppliers of components and services around the world in product creation and realization processes that serve consumer markets globally.

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[1] Some researchers in international business have argued that few if any product markets are truly global, and that most products are still produced and marketed regionally or nationally. Clearly, there are examples of industries for which that is the case, but in a number of major product markets (e.g., consumer electronics, automobiles, software, and financial services) production of products for marketing globally is today a common practice. In addition, as the architectural perspective on product markets makes clear, development and production of components for many final products (e.g., engines and transmissions for automobiles) is increasingly a global undertaking in order to maximize economies of scale and distribution.

[2] The success of Amazon.com and other Internet booksellers in quickly becoming a major force in book retailing in the US and Europe is a case in point.

Rising customer sophistication means that growing numbers of consumers around the world are becoming more familiar with high value-added products, more knowledgeable about how those products can be used to benefit their lives, and more desirous of well differentiated and higher performing products that are better suited to their individual lifestyles. In their efforts to meet increasingly sophisticated consumer demands, firms are also becoming more sophisticated in the range of product and process components they want to buy in order to better differentiate the products they offer to various markets. Firms are also demanding more rapid technological upgrading of the components they buy in order to continuously improve product performance, while at the same time the prices firms are willing to pay for product and process components globally are continually falling.

As the impacts of increasing consumer sophistication work their way up the supply chains of firms globally, more and more of the value-added in goods and services is coming from their *knowledge-content*. In effect, to create and realize competitive product offers in the global economy, firms must access and incorporate into their product offers increasingly broader and more sophisticated knowledge about design, manufacture, logistics, and support.

Incentives for Cooperation in Adopting Standard Modular Architectures and Common Components

Along with the foregoing competitive conditions come a number of new incentives for extended technological cooperation among firms, especially in the form of incentives to adopt standard modular architectures and common components. We next consider a number of demand-side incentives for firms to adopt modular architectures as an integral part of a new *strategic logic* (Sanchez, Heene & Thomas, 1996) for meeting rising consumer demands and expectations in the global economy. We then consider ways in which the global economy is also creating new supply-side incentives for firms to cooperate in adopting *standard modular architectures and common components* that can significantly extend the strategic benefits of using modular architectures to serve rising consumer demands globally.

Demand-side Incentives

The increasing size, scope, and sophistication of consumer demand globally for high value-added products promise growing rewards for firms that can create and realize greater product variety, learn faster and more precisely about customer preferences, continually introduce higher performing products, and offer well-differentiated and high-performing products at increasingly competitive prices. We next consider how the use of modular product and process architectures can greatly improve the ability of a firm to meet and profit from the global economy's escalating consumer expectations.

Leveraging greater product variety The ability to "mix-and-match" components in a modular product architecture can enable a firm to configure much greater product variety at much lower cost than creating a comparable level of product variety based on "one-off" product designs. This flexibility of modular product architectures is now being used by a growing number of firms to offer expanded ranges of product models in industries as diverse as automobiles, consumer electronics, home appliances, software, banking services, and power tools (Langlois & Robertson, 1992; Sanchez, 1999; Sanchez & Mahoney, 1996). For example, Sony and its Aiwa subsidiary used modular architectures to leverage more than 250 different Walkman and Discman models in the US during the 1980s (Sanderson & Uzumeri, 1997). The leveraging of modular product variations to explore market preferences and price sensitivities can enable a firm to learn about consumer preferences in greater detail and thus to segment markets more finely and accurately than their competitors (Sanchez, 1999).

Mass customization (Pine, 1992) — the configuration of a product variation for a specific customer based on the customer's choice from a menu of available versions of modular components — allows a firm to treat each customer as a "market segment" composed of one consumer. A well known example is Dell Computer's configuring customized personal computers based on a consumer's choice of modular component variations (microprocessors, hard disk drives, memory cards, monitors, etc.). *Product personalization* takes mass customization one step further by including in a modular product at least one unique component that is made specifically for an individual customer. Much of the personalized clothing and footwear being sold today, for example, consists of one or more truly personalized components (the legs of trousers or the insole of a shoe) that are made to fit an individual customer's shape and size and that are combined with standard component variations (standard pockets and zippers, or standard shoe soles and leather uppers) to create a personalized product. Mass customization and product personalization enable firms to charge premium prices for their modular products or to use customization and personalization to achieve superior product differentiation at competitive prices.

Real-time market research When a firm can use the flexibilities of its modular product and process architectures to leverage large numbers of product variations based on different mix-and-match combinations of modular components, it may adopt an alternative approach to researching consumer preferences known as real-time market research (Sanchez & Sudharshan, 1993). Rather than investing time and money in consumer surveys, focus groups, and other traditional market research methods, a modular architectural firm will produce and offer to consumers small lots (perhaps a few thousand) of products based on mix-and-match combinations of modular components to determine which product variations consumers actually prefer — and at what price points they can be sold most profitably. Both Sony and Nike now maintain a global chain of company stores — sometimes referred to as antennae shops — in which they continually test consumer reactions to a stream of new modular product variations. Firms that can use modular product architectures in this way may quickly detect and respond to shifts in consumer preferences within a product category or movements of consumers from one product category to another (Sanchez, 1999).

Combining the use of modular architectures to mass customize products with Internet marketing also makes it possible to develop deep insights into consumer behaviors as they consider and make trade-offs between alternative product variations and prices. The Buick product group within General Motors, for example, offers consumers a website where they can select various component-based options for a Buick (e.g., sound systems, climate control systems, interior trim packages, etc.) and receive pricing information for a model so equipped. By tracking consumers' choices of options, their responses to pricing information for those options, and the trade-offs that consumers make when weighing alternative options-and-price combinations, Buick is developing deep insights into the preferences of consumers for various component-based options at various price levels.

Using modular architectures as platforms for building customer relationships In the increasingly competitive product markets of the global economy, modular architectures can be used as platforms for building long-term customer relationships and loyalty by delivering to consumers the benefits of scalability, upgradeability, extensibility, and connectivity. Several examples from personal computers help to illustrate these benefits.

Scalability is provided by a modular architecture that allows the "capacity" of a product in some important aspect of its performance to be increased by "plugging and playing" one or more additional modular components. The memory of most personal computers today is scalable, for example, because the memory can be increased by plugging additional memory cards into the PC bus or by adding additional peripheral storage devices like hard disks. Firms using modular architectures can then sustain a customer relationship by providing scalable components to customers as their needs evolve and require greater capacity.

Upgradeability enables a consumer to increase a given performance level of a product by changing a key component responsible for that aspect of a modular product's performance. For example, many personal computers are designed today to allow the replacement of a current microprocessor with faster microprocessors as they become available. Providing customers with a stream of higher performing components that upgrade product performance offers another way to sustain the customer relationship and increase customer loyalty.

Extensibility gives consumers the ability to add new functionalities to an existing product by adding new components to a modular product architecture. Today's personal computers allow a number of additional modular components like fax cards, video cards, and cards or software for digitally encoding music to be plugged and played to expand the number of functions the personal computer can perform for the customer. Customer relationships can be strengthened and expanded by developing new modular components that add new functionalities to existing products.

Connectivity enables a consumer to plug and play a number of different products together in ways that enhance the benefits a customer derives from each product. For example, personal computers today include FireWire ports that allow consumers to connect digital cameras and audio CD players to their computers so that they can print and store photographs, edit videos, store digital music, and otherwise manipulate images and sound for professional or personal purposes. Providing consumers with an array of modular products that plug-and-play with a customer's current product provides yet another way of sustaining a customer relationship over the long term.

Faster introductions of higher performing products A modular product architecture can usually be designed today to accommodate technologically improved components that are expected to become available in the future — i.e., within part or all of the expected commercial lifetime of the product architecture. The ability to introduce improved components directly into a modular product architecture (without having to make design changes in the other components used in the product architecture) enables the rapid introduction of higher performing product models to markets as soon as improved components become available. Sony's use of a modular product architecture for its original series of HandyCam video cameras, for example, enabled the firm to bring four upgraded models to market within a 22-month period by directly incorporating improved components into the original HandyCam product architecture (Sanchez & Sudharshan, 1993).

Lower design, production, distribution, and service costs Leveraging a potentially large number of product variations from a single modular product architecture can substantially reduce design and development costs for each new product variation introduced. Cost savings can also be realized when the same component of a given type is used in common across all or many of the models in a family of products, because that component can then be produced or purchased in large numbers. A design strategy of using common components wherever possible (i.e., so long as effective product differentiation is not compromised) reduces the variety of components and parts that must be held in assembly-line and spare-parts inventories and also reduces service training costs incurred in supporting a firm's products. General Electric's different stove models, for example, are differentiated by cooktops and control panels added in the last stages of the assembly process, while high-speed production lines assemble the common components used in all GE's stove models.

Supply-side Incentives

A prominent feature of the global economy is the explosive growth of the use of the Internet and firm-based intranets to radically expand the *quick-connectivity* (Sanchez, 1996) and *interoperability* (Hald & Kosynski, 1993) of firms around the world. As more firms become electronically connected to each other, significant incentives are being created for firms to cooperate in adopting standard modular architectures and common components in their efforts to serve consumer demands in the global economy. We therefore now consider how the use of standard information formats, standard software, and standard modular architectures are creating quick-connectivity and interoperability among firms globally. We then discuss ways in which adoption of standard modular architectures and common components enables quick-connected, interoperable firms to access an expanding global network of component-based expertise that is becoming a primary driver of the increasing knowledge content of many firms' product offers.

Standard information formats to support commercial transactions An essential first step in electronically connecting one firm to others is the adoption of standard formats for exchanging information between firms' computer systems — often referred to as *electronic data integration* (EDI). Important industry-level EDI initiatives have established standard information formats to support commercial transactions globally. These cooperative initiatives include defining standard identifications for individual products through use of bar-coded universal product codes (UPC), the use of industry-standard purchase orders and shipping documents, and the adoption of standard data fields for encoding personal financial information on the magnetic strip on consumers' credit cards and cash cards.

Standard software to support development and service activities Many firms and a growing number of industries are now adopting or extending the use of standard software that enables firms to "quick connect" to and work with other firms in distributed development and service activities (Sanchez, 1996). In its Ford 2000 initiative, for example, Ford adopted a standard computer-assisted design (CAD) software program that is used worldwide by its own product design centers and by its first-tier component suppliers. Use of a standard CAD system enables Ford and its component suppliers to work together on the same component design files and to pass those files from one design center to another around the world in a 24-hour-a-day product development process. Similarly, many firms are now beginning to create CD-ROM or Internet-accessible electronic files for all their service procedures and parts lists. Providing qualified service providers around the world with standard software for accessing those files helps product firms to configure global service infrastructures to support their products.

Standard modular architectures and common components To achieve true "interoperability" (Hald & Kosynski, 1993) among firms in developing, producing, and supporting products globally, however, requires more than just standard information formats and standard software for processing information. In a basic sense, standard information formats and software provide a solution to the problem of *how* firms can connect and communicate with each other globally, but they do not address the problem of defining and coordinating *what* various interconnected firms will do within a global value chain. Adopting standard modular architectures is therefore the third essential step in achieving true interoperability among firms, because standard modular architectures provide a framework for defining, allocating, and coordinating the tasks to be performed by each participant in a wired value chain.

As we have discussed earlier, architectures decompose the overall design of a product or process into functional components and then specify the interfaces between the components that enable the components to work together as a system. The adoption of a standard modular architecture by a number of cooperating firms creates demand for the specific types of functional components required by that architecture. The cooperating firms may decide to specialize in the development and production of certain components and to supply those components to all firms using the standard architecture. Moreover, if the collective demand of those firms for specific component types is large enough, potential suppliers may also decide to develop and produce specific components for the standard modular architecture.

The adoption of a standard modular architecture typically creates a stable technical infrastructure in which certain types of standard components that are not important in differentiating products will be used in common across all or many of the products offered by the cooperating firms. The overall costs of developing and producing *common components* for a standard modular architecture may fall significantly when those activities become concentrated in specialist component suppliers that can achieve significant economies of scale in development and production. Chrysler and General Motors, for example, have cooperated in adopting common gear designs for the drive trains of their vehicles and even established a jointly owned factory to supply common gear components to both companies.

Some components in a standard modular architecture will be important sources of product differentiation, however, and the adoption of a standard modular architecture by several firms will increase demand for a growing range of variations in the types of components that can be used to differentiate various firms' products. This increased demand encourages component specialist firms to invest in providing both greater variety and more frequent upgrading of components, while the increased scale of their development and production activities may also lead to lower costs per component variation offered. The adoption of a standard modular architecture for personal computers in the 1980s, for example, stimulated both an increase in the variety of components available from specialist suppliers and the rate at which the performance of those components was improved.

Both through the lowered costs of common components and through the increased variety and more rapid performance improvements of differentiating components, firms that cooperate in adopting a standard modular architecture are often able to configure more product variations — and to do so at lower unit costs — than firms that use proprietary architectures, even when those architectures are modular.[3]

Standard knowledge architectures and accelerated technological learning

When cooperating firms adopt a standard modular product architecture, they are

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[3] Of course, a large firm that uses a proprietary modular architecture may be able to realize many of the benefits that firms using a standard modular architecture achieve when the volumes of its own common components and differentiating components are substantial.

also effectively standardizing the component interfaces of the architecture.[4] When the component interface specifications in a modular architecture are *standardized* — i.e., not allowed to change over some period of time — they create a stable *technical infrastructure* that defines the required inputs and outputs of all components in the current standard architecture (Sanchez & Mahoney, 1996). The stable technical infrastructure provided by the standardized component interface specifications in a modular product architecture makes it possible for development tasks to be carried out *concurrently and independently* by a network of component development firms. As long as all firms developing components for the standard architecture conform to the standardized input and output specifications for components in the architecture, the component development process carried out in one firm is not dependent on the component development processes underway in other firms. Because of this, component development in support of a standard modular architecture may come to consist largely of self-managing activities undertaken by a number of specialist firms and coordinated by the *information structure* provided by the standardized component interface specifications (Sanchez & Mahoney, 1996).

Moreover, by adopting a standard modular architecture, a firm may gain access to the extensive knowledge developed by firms that specialize in developing specific components for the standard architecture. A firm that develops the *architectural knowledge* (Sanchez & Mahoney, 1996) needed to understand and use the standardized interface specifications of a standard modular architecture does not have to develop internally all the knowledge required to create components for the architecture. Rather, it can focus on configuring new product variations within the standard modular architecture that are based on modular component variations provided by component specialists, plus perhaps one or a few components in which it maintains world-class development and production capabilities internally (Venkatesan, 1992). The adoption by GE Fanuc Automation of standard modular architectures for its industrial controllers has enabled hundreds of component specialists around the world to develop a growing range of modular components that "plug and play" in GE Fanuc's standard architectures (Sanchez & Collins, 2001).

The standardized interface specifications in a standard architecture create, in effect, an industry-level *standard knowledge architecture* in which firms specialized in specific components develop semi-autonomous, component-based *knowledge domains* that facilitate accelerated technological learning about

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[4] Since an architecture consists of a decomposition of a design into functional components and the specification of the interfaces between components in the architecture, standardizing an architecture necessarily implies standardizing the interface specifications in the architecture.

modular components. The stable technical infrastructure provided by standardized component interfaces means that component development firms do not have to invest development resources in revising component designs to meet diverse or unstable interface specifications — an activity that can consume up to 80% of development resources (Sanchez & Collins, 2001). Instead, firms can focus their available development resources on creating a wider range of component variations and higher performing components that conform to the standardized component interfaces. This ability to focus on extending the variety and performance of modular components often significantly accelerates technological learning in an industry that has adopted a standard modular architecture. It is no coincidence therefore that the industries widely regarded as the most technologically dynamic — e.g., computers, software, and telecoms — are also industries with the highest levels of voluntary adoption of standard modular architectures (Sanchez, 2000).

From Proprietary Architectures to Open-System Modular Architectures

Firms in the global economy increasingly follow an evolutionary path that begins with creation of a proprietary modular architecture, then seek cooperation with other firms to define and adopt an industry-standard modular architecture, and may eventually lead to adoption of an *open-system* standard modular architecture.[5] The move to open-system architectures is often accompanied by a shift from *producer-controlled product differentiation* to *customer-controlled product differentiation* (Sanchez, 1999) that fundamentally changes the nature of competition in a product market and calls for new cooperative strategies to compete effectively.

Forces Driving the Evolution of Modular Architectures

To understand the emergence of open-system standard modular architectures in a product market, we now take a closer look at the forces that drive the evolution of modular architectures in a product market.

As a new product market begins to develop around a new product concept, some designs for the new product concept will be more successful in supporting

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[5] An open-system standard modular architecture is one in which the standard component interfaces are publicly available, so that any interested firm can begin to develop and produce modular components that can be plugged and played in the standard modular architecture.

customers' approaches to using the new product. Eventually a *dominant design* for the new product concept will emerge that is most successful in meeting customers' preferences for using the new product (Abernathy & Clark, 1985; Clark, 1985). The emergence of a dominant design is a pivotal event in the evolution of product architectures, because it establishes the "core" functionalities that the new product architecture must provide, the decomposition of those functionalities into specific kinds of components, and the modes of interactions of those components within the product architecture (Sanchez, 1995b). Emergence of a dominant design enables producers to define a standard product architecture that is widely acceptable to consumers, and this enables standardization of functional components that can be mass-produced to lower costs.

The inherent performance and variety limitations of an early standard product architecture will eventually lead some firms to try to create new product architectures capable of accommodating more component variations or even new kinds of components. At this stage, important *modular architectural dimensions* of product competition will emerge as some firms try to create modular product architectures that can accommodate a wider range of component variations than the product architectures created by their competitors. Combining their market insights and product design capabilities, some firms will create proprietary modular product architectures with component interface specifications that allow mixing and matching of a wide range of component variations to create differentiated products. Component interface specifications may also be created to support future introductions of upgraded components as a means of quickly and efficiently upgrading product performance.

If a firm can fully use the superior flexibility of its proprietary modular product architecture to establish and maintain broad market coverage, as IBM did with its 360 modular architecture in the 1960s, the firm's modular product architecture may become a *de facto* industry standard architecture, even though the firm may maintain full control and confidentiality of the interface specifications in its proprietary modular architecture. However, several positive network externalities associated with product architectures may eventually encourage firms with successful proprietary architectures to make their architectures an "open system" by sharing interface specifications with competitors or by cooperating in developing industry-wide standard component interface specifications. In addition to the positive externalities we have already discussed earlier in this paper, adopting a standard product architecture in an industry can both lower costs for producers and increase convenience for consumers by allowing standardization of essential complementary goods like diskettes for computers, fuel types for automobiles, and signal protocols for telecommunications products. Firms can also benefit from having ready access to the human skills needed to use and maintain an industry's products when technical education and training programs can be focused on a common industry standard product architecture.

In addition to supply-side incentives to adopt open-system modular product architectures, there may be additional demand-side incentives to adopt an open-system industry standard modular architecture. Corporate customers may be wary of purchasing products based on proprietary architectures that would make them dependent on a single manufacturer for product upgrades, replacements of components, service, and complementary goods. Thus, even if a proprietary product architecture offers superior product performance, many potential purchasers may decide that the risks of becoming locked into a single-source proprietary product architecture may outweigh the benefits of the product's superior performance. Such concerns may force a firm with a high-performing proprietary architecture to accept second-source agreements that require them to reveal part or all of the interface specifications in their proprietary architectures to one or more competing firms.

Potential customers' fears of lock-in to proprietary architectures may even force a firm to make a strategic shift from a proprietary to an open-system product architecture. Despite the superior performance of Digital Equipment Corporation's proprietary Alpha microprocessor architecture in the early 1990s, for example, concerns of its key customers about lock-in and lack of connectivity with computers based on other microprocessors eventually led Digital to shift to an open architecture strategy. Digital subsequently redesigned its Alpha microprocessor to be interoperable with other microprocessors (especially the *de facto* industry standard microprocessors from Intel) and to support a number of different operating systems. Similar concerns led Sun Microsystems to adopt a strategy of offering a Unix-based open architecture for workstations that gave Sun's customers interconnectivity, upgradeability, access to large numbers of competitively priced applications programs, and widely available service and support.

Furthermore, some product markets may have important sophisticated customers that fully understand the functionalities that specific components in a modular product architecture can provide and therefore may be able to determine the combination of component variations that would provide the exact set of functionalities they want to have. Such customers may demand open-system modular product architectures that allow them to mass-customize their desired product variation by configuring a preferred combination of components within the modular architecture. In modular product markets as diverse as consumer electronics, pagers, sport bicycles, personal computers, banking services, and power tools, some producers are increasingly pursuing open-system modular strategies that allow consumers to choose modular component variations within an open-system architecture to configure customized products that best suit their individual preferences.

Shifting Control of Product Differentiation from Producers to Customers

Adopting open-system modular product architectures that let customers directly select the combinations of component variations that best suit their individual preferences constitutes a strategically important shift from *producer-controlled product differentiation* to *customer-controlled product differentiation*. This shift in the locus of differentiation decisions fundamentally transforms the nature of competition in product markets and the ways in which modular architectures are used strategically (Sanchez 1999).

In producer-controlled differentiation, producers research markets to identify the sets of consumer preferences shared by different segments of the market. Producers then decide which combinations of component variations would be most effective in serving the preferences of targeted market segments. In this traditional approach to producer-controlled differentiation, product market success results when a producer has superior capabilities (or luck) in aggregating consumer preferences into well-defined market segments and in developing product variations that appeal strongly to its targeted market segments.

Eventually, some firms in a product market may recognize that adopting an open-system modular product architecture makes it possible to pursue a new competitive game. These firms will, in effect, "unbundle" their producer-determined combinations of components and allow customers to select their own combinations of modular components that most nearly satisfy their individual preferences. To support this shift to customer-controlled product differentiation, producers may also have to invest in flexible manufacturing systems to support the mass customization of products (Pine, 1992). New direct marketing approaches and door-to-door distribution will often be established to bypass the bottleneck of inventory-driven distribution channels that are ill-suited to gather product specifications from many individual customers and to deliver customized products to individual customers.

Once customer-controlled product differentiation becomes widespread in an open-system modular market, the opportunities for profiting from products based on producer-controlled differentiation may become quite limited. As more customers become accustomed to ordering individually customized products, fewer customers may be willing to compensate producers for their "standard" differentiated products. Furthermore, because many common components used in open-system modular architectures can be mass produced and will therefore benefit from economies of scale, prices of mass-customized products may well fall to price levels that are competitive with producer-differentiated products.

Conclusion: Cooperative Strategies in Open-System Standard Modular Markets

When product markets evolve to open-system standard modular architectures and component-based product differentiation decisions shift to customers, firms must adopt new kinds of strategies to compete profitably. These new strategies invite new forms of interfirm cooperation on a number of dimensions.

In open-system modular markets, most (and perhaps all) firms will abandon efforts to be comprehensive developers of technologies, components, and products. Rather, many firms will try to build competences in only one or a few key technologies and components in which they believe they can consistently achieve superior performance and cost, while outsourcing or partnering in the development and production of other technologies and components. Such firms must develop new cooperative skills needed to coordinate a network of component specialist firms. While some firms may elect to form long-term alliances with a few committed component suppliers, other firms may choose to pursue a more flexible organization strategy by developing modular component interface specifications that invite and facilitate development of new components by specialist firms worldwide.

To serve customers capable of specifying their own customized products, a firm must be capable of establishing and managing interactive marketing channels that let potential customers efficiently communicate their preferred product specifications to the firm. Since not all customers will be equally competent, confident, or motivated to configure their own customized products, however, producers must also learn how to provide "turnkey" system configuration services for customers who can only define the functional requirements for the products they need, but cannot "translate" those requirements into an appropriate set of component choices within an open-system architecture. Providing the most effective customized solutions for individual customers often requires using a broad mix of modular components — some of which must be sourced from competing firms or component suppliers with whom a producer has not previously had dealings. Thus, to achieve the greatest flexibility in customizing products within open-system modular architectures, producers must be willing and able to cooperate with the suppliers of the most appropriate modular components available in the marketplace. Producers may also have to expand their cooperation with new kinds of market intermediaries, like third-party value-added vendors who are important channels for customizing products and providing support services to customers.

We are seeing more and more product markets enter an advanced stage of modular evolution accompanied by the emergence of open-system modular product architectures. In such markets, a firm's competitive survival is likely to depend on sustaining cooperative strategies that enable the firm to *simultaneously*

(a) access a global pool of component developers and producers that enable the firm to use an open-system standard modular product architecture to configure greater product variety at lower costs than competitors;
(b) achieve the manufacturing, logistics, and service flexibilities needed to support mass-customization of products for individual customers globally;
(c) maintain focused technology leadership in development and production of one or more product or process components that are effective in differentiating the firm's products;
(d) provide customer support to less sophisticated customers to help them select the combinations of modular component variations in an open-system modular architecture that will best suit their individual functional requirements and cost constraints.

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