CHAPTER ELEVEN

MODULARITY, FLEXIBILITY, AND KNOWLEDGE MANAGEMENT IN PRODUCT AND ORGANIZATION DESIGN

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INTRODUCTION

Daft and Lewin identify the "modular organization" as a new paradigm that has as its premise "the need for flexible, learning organizations that continuously change and solve problems through interconnected coordinated self-organizing processes" (1993: i). This paper investigates approaches to ***managing knowledge*** in a firm's product-creation processes that facilitate specific forms of "coordinated self-organizing processes" capable of improving a firm's ***strategic flexibility*** to respond advantageously to a changing environment (Sanchez, 1993, 1994b, 1995). To do so, we investigate concepts of ***modularity*** in both product designs and organization designs.

We explain how advanced technological knowledge about component interactions can be used to fully specify and standardize the component interfaces that make up a modular product architecture, creating a nearly independent system (Simon, 1962) of "loosely coupled" components. We then suggest that just as some work may be coordinated by specifying standard operating procedures (Cyert and March, 1963) that govern ***processes*** directly, much work in product development may be coordinated by specifying standardized component interfaces that govern the ***outputs*** of component development processes. In essence, the standardized component interfaces in a modular product architecture provide a form of ***embedded coordination*** that greatly reduces the need for overt exercise of managerial authority to achieve coordination of development processes, thereby making possible the concurrent and autonomous development of components by ***loosely coupled organization structures*** (Orton and Weick, 1990). Thus, using technological knowledge to create ***modularity in product designs*** becomes an important strategy for achieving ***modularity in organization designs.***

This paper is organized in the following way. The next section builds on Simon's (1962) notion of "nearly decomposable" systems by proposing that product designs and organization designs follow the fundamental principles of decomposition.

We then investigate modularity in product and organization designs. We suggest that although organizations ostensibly design products, it can also be argued that ***products design organizations,*** because the coordination tasks implicit in specific product designs largely determine the feasible organization designs for developing and producing those products.[1]

The following section considers how learning processes create ***information structures*** in product development processes, and it evaluates the characteristic information structures and resulting learning efficiencies of three models for organizing product development processes: sequential development, overlapping problem solving, and modular product design.

We conclude by suggesting that the emerging prominence of modular product designs is being accompanied by new knowledge management strategies (Grant, 1993; Sanchez, 1996c) that allow product creation to be carried out more effectively through flexible, "modular" organization structures.

NEARLY DECOMPOSABLE SYSTEMS

A complex system – whether product design or organization structure – consists of parts that interact and are interdependent to some degree. Simon (1962) argues that ***hierarchy*** is an organizing principle of complex systems, which are essentially composed of interrelated subsystems that in turn have their own subsystems, and so on.

This paper applies Simon's (1962) ***structural*** conception of hierarchy in complex systems to the analysis of product designs and of organizational processes for developing new products. In so doing, we use a more general conception of "hierarchy" than that usually invoked in organizational economics and strategic management (e.g., Mahoney, 1992b, 1992c; Williamson, 1975), where hierarchy typically denotes subordination to an ***authority*** relationship. Our interest here, however, is in understanding hierarchical systems for creating new products in which there is ***little or no overt exercise of managerial authority.***[2]

In this discussion, "hierarchy" refers to a decomposition of a complex system into a structured ordering of successive sets of subsystems, in the manner suggested by Simon (1962) – i.e., a partitioning into relationships that collectively define the parts of any whole. We suggest that hierarchy, in this structural sense, may be a feature of both designs for products and designs for organizations that create products (Sanchez, 1995, 1996b).

Simon (1962) further defines a ***nearly decomposable system*** as one in which interactions among subsystems are weak (but not necessarily negligible). The interactions between the divisions of a multidivisional organization are representative of a nearly decomposable system (Mahoney, 1992a; Williamson, 1975). The tasks within a multidivisional firm are intentionally designed to require low levels of coordination so that they can be carried out by an organizational structure of quasi-independent divisions functioning as ***loosely coupled subsystems*** (Weick, 1976).

An important property of this structural hierarchical decomposition is that the impacts of environmental disturbances may be localized within specific subsystems, increasing the survivability and adaptability of the overall system in a turbulent environment (Orton and Weick, 1990). Extending these insights to product designs and organizations that create new products, we suggest that new approaches to decomposing and structuring product designs have enabled the adoption of more structurally decomposed – and thus more adaptable – organization designs for creating products.

Modularity in Product and Organization Designs

Product designs differ fundamentally in the degree to which a design has been decomposed into "loosely coupled" vs. "tightly coupled" components. The degree to which components are loosely coupled or tightly coupled in a product *design* depends on the extent to which a change in the design of one component requires compensating design changes in other components. *Modularity* is a special form of design which intentionally creates a high degree of independence or "loose coupling" between component designs by standardizing component interface specifications. This section explains how modular design achieves the loose coupling of component designs and in the process creates an *information structure* that can provide *embedded coordination* of loosely coupled component development processes (Sanchez, 1995).

Modular product designs

A component in a product design performs a function within a system of interrelated components whose collective functioning make up the product. Relationships between components are defined by the specifications of inputs and outputs linking components in a design,[3] and a complete set of component interface specifications constitutes a *product architecture* (Abernathy and Clark, 1985; Clark, 1985).

Traditional engineering design follows a methodology of constrained optimization, which tries to obtain the highest level of product performance within some cost constraint or the lowest cost for a product meeting a minimum performance constraint. This design methodology typically leads to product designs composed of highly integrated, tightly coupled component designs. Specifications of input and output interfaces between components must therefore reflect the idiosyncratic characteristics of each tightly coupled component design. As a consequence, *processes* for developing tightly coupled component designs require intensive managerial coordination, since a change in the design of one component is likely to require extensive compensating changes in the designs of many interrelated components. Thus, product designs composed of tightly coupled components will generally require development processes carried out in a *tightly coupled organization structure* coordinated by a managerial *authority hierarchy*, an organization design typically achieved within a single firm.

Some firms, however, are now using an alternative design methodology that intentionally creates loosely coupled component designs by specifying *standardized component interfaces* that define functional, spatial, and other relationships between components that, once specified, are not permitted to change during an intended period in a product development process. The "intended period" during which standardized component interfaces are not permitted to change may range from key stages in the development of a new product architecture (Cusumano and Selby, 1995) to the entire commercial lifetime of a product family (Sanchez, 1995). Standardizing component interface specifications during a period of time allows processes for developing component designs to become loosely coupled, because they can be effectively coordinated simply by requiring that all developed components conform to the standardized component interface specifications.[4] Thus, controlling the required *output* of component development processes by standardizing component interfaces permits effective coordination of development processes without the continual exercise of managerial authority. The specification for standardized component interfaces provides, in effect, an *information structure* (Radner, 1992) that coordinates the loosely coupled activities of component developers.

A *modular product architecture* (Sanchez, 1994a; Ulrich and Eppinger, 1995) is a special form of product design that uses standardized interfaces between components to create a *flexible* product architecture. In modular product design, the standardized interfaces between components are specified to allow for *a range of variations* in components to be substituted into a product architecture. *Modular components* are components whose interface characteristics are within the range of variations allowed by a modular product architecture. The modular architecture is *flexible* (Sanchez, 1995) because product variations can be leveraged by substituting (Garud and Kumaraswamy, 1993) different modular components into the product architecture without having to redesign other components. This loose coupling of component designs within a modular product architecture allows the "mixing and matching" of modular components to give a potentially large number of product variations distinctive functionalities, features, and/or performance levels (Sanderson and Uzumeri, 1990; Sanchez, 1994a; Ward et al., 1995).

Modular product architectures can be an important source of *strategic flexibility* (Sanchez, 1995) when they enable a firm to respond more readily to changing markets and technologies by rapidly creating product variations based on new combinations of new or existing modular components. The standardized component interfaces of a modular product architecture also enable the coordination of a loosely coupled organization structure linking geographically dispersed component developers. Thus, a firm may be able to use a modular product architecture to coordinate a global network (Kogut and Bowman, 1995; Kogut and Kulatilaka, 1994) or "constellation" (Normann and Ramirez, 1993) of component developers and suppliers to source a broad range of component variations, thereby further enhancing the ability of the firm to leverage new product variations. In this way, "loose coupling [within a product architecture] facilitates continuous change" (Spender and Grinyer, 1995) by improving the ability of a firm to generate new product variations. As table 11.1 indicates, modular product architectures that allow mixing and matching[5] of modular components are now appearing in diverse product markets (Sanderson and Uzumeri, 1990; Sanchez, 1991).

Table 11.1 Examples of products with modular designs.

Products	Form of modular product design	References
Aircraft	Common wing, nose, and tail components allow several models to be leveraged by using different numbers of fuselage modules to create aircraft of different lengths and passenger/freight capacities (used by Boeing, McDonnell-Douglas, and Airbus Industries).	Woolsey (1994)
Automobiles	Automakers have long used many basic modular components specified by the Society of Automotive Engineers.	Nevins and Whitney (1989)
	Some automakers use common (modular) components in many different models. Also, the Taurus platform design is leveraged to provide a basis for the Taurus and Mercury Sable sedans and wagons and for the Ford Taurus Windstar minivan.	*Automobile* (1994)
	Ford is converting its auto and struck engines to modular engine designs with high levels of common (modular) parts. The 4.6 L V-8 introduced in 1992 was Ford's first modular engine.	*Ford Engineering World* (1990)
	Chrysler's LH car designs are modular. Several models have been leveraged from common power train and engine components. The interior of each model is composed of four easy-to-install units that arrive ready-built from separate suppliers. The Chrysler Neon uses numerous modular assemblies.	Tully (1993)
Consumer electronics	Over 160 variations of the Sony Walkman were leveraged by "mixing and matching" modular components in a few basic modular product designs.	Sanderson and Uzumeri (1990)
	Several upgraded models of Sony HandyCam video cameras were leveraged from an initial system design by successively introducing improved modular components.	Sanchez (1994a)
Household appliances	General Electric leverages several models of dishwashers by installing different modular doors and controls on common assemblies of enclosures, motors, and wiring harnesses.	Sanchez and Sudharshan (1993)
Personal computers	Personal computers often consist largely of modular components like hard disk drives, flat screen displays, and memory chips, coupled with some distinctive components like a microprocessor chip and enclosure.	Langlois and Robertson (1992)
Software	Software designs are creating modules of routines which can be combined to create customized applications programs.	Cusumano (1991)
	Software designers attain modularity through loose coupling. The objective is often to minimize coupling – i.e., to make modules as independent as possible. Loose coupling between modules signifies a well-designed system. Modular programming (1) allows one module to be written without knowledge of the code in another module (a decomposition using an "information hiding" regime), and (2) allows modules to be reassembled and replaced without design of the whole system. Separating *action* (what the module does) and *logic* (how the module accomplishes the action) is a "composite" approach to software engineering that has been deployed by NASA and GTE, among others.	Parnas, Clements and Weiss (1985)
	Software for designing application-specific integrated circuits (ASICs) provides modular circuit elements which can then be linked together to provide the specific functionalities needed to customize an ASIC for a specific product application.	von Hippel (1994)
Test instruments	Philips created a flexible chassis for receiving modular components which permit the configuration of large numbers of specialized oscilloscopes for testing various kinds of electronic products.	*Electronics* (1986)
Power tools	Black and Decker designed its entire line of power tools in the 1980s to incorporate a high degree of common modular components.	Utterback (1994)

Table 11.1 (*cont'd*)

Modular organization designs

Specifying the required ***outputs*** of component development processes permits those processes to be partitioned into tasks (von Hippel, 1990) that can be performed ***autonomously and concurrently*** by a loosely coupled structure of development organizations. In effect, the ***information structure*** provided by the standardized component interface specifications of a modular product architecture provides a means to embed coordination of loosely coupled component development processes. The information structure of a modular product architecture thus provides the "glue" of embedded coordination that allows a loosely coupled development organization to achieve syntheses (Spender and Grinyer, 1995) in the form of developed products.[6]

A loosely coupled product creation organization in which each participating component development unit can function autonomously and concurrently under the embedded coordination of a modular product architecture appears to correspond closely to Daft and Lewin's notion of ***modular organizations*** "that continuously change and solve problems through interconnected coordinated self-organizing processes" (1993: i). A firm using a modular product architecture to coordinate development processes has a means to quickly link together the resources and capabilities of many organizations to form product development "resource chains" that can respond flexibly – i.e., broadly, quickly, and at low cost (Sanchez, 1995, 1996b) – to environmental change.

Models for Managing Knowledge and Learning in Product Creation

Product development projects can be thought of as "programmed" innovation in which firms create new products by applying existing knowledge and creating new knowledge about components and their interactions. To create the information structure of fully specified and standardized component interfaces in a modular product architecture requires a high level of architectural knowledge (Sanchez, 1996c; Wright, 1994) about how components function and interact in a product. To the extent that a firm has inadequate knowledge of components and their interactions, creating a new product architecture requires learning by experimenting (Baldwin and Clark, 1994) with new component designs and alternative arrangements of components.

Innovation during product development may therefore involve (i) creating new information about the functions components can perform, which implies learning about components *per se*, or (ii) creating new information about the ways components interact and can be configured, which implies learning about product architectures (Henderson and Clark, 1990). Extending the notion of learning at component and architectural levels, figure 11.1 identifies four modes of learning – radical, architectural, modular, and incremental – that can occur in product innovation process (see Henderson and Clark, 1990).

Learning about component interactions and configurations	Learning about component functions and designs: Moderate	Learning about component functions and designs: Significant
Moderate	**Incremental learning at the component level** Incremental learning through component development leads to limited functional improvements and design variations in components used within an existing product architecture.	**Modular learning at the component level** Learning about new kinds of component technologies leads to significant changes in feasible component functions and designs that can be accommodated within an existing product architecture.
Significant	**Architectural learning** Learning about new product market opportunities leads to new product architectures based on changes in the ways existing kinds of components are combined and configured in product designs.	**Radical learning at architectural and component levels** Learning about new market opportunities and new product and component technologies leads to major changes in both kinds of components used and ways components are configured to form a product architecture.

Figure 11.1 Modes of learning in product creation processes.

Research in strategy has often emphasized the challenges to organizations of "radical" learning (Dewar and Dutton, 1986). More recently, attention has also been paid to the importance of "architectural" learning (Morris and Ferguson, 1993; Henderson and Clark, 1990). Significant benefits may also be realized, however, by effectively leveraging new products based on "modular" or "incremental" forms of learning that can take place within an existing product architecture (Sanchez, 1995, 1996b). All these forms of learning are vital to organizational renewal and development, but not all processes for learning during product development are equally efficient. This section considers ways in which processes for architectural, modular, and incremental learning during product development may be managed to improve the efficiency of both component and architectural levels of learning.

Much recent research into improving the effectiveness and efficiency of product development has focused on processes for knowledge creation and information transfer in product creation projects (e.g., Clark and Fujimoto, 1991; Wheelwright and Clark, 1992). The product creation process generally consists of product concept development, feasibility testing, product design, component development processes, pilot production, and final production (Takeuchi and Nonaka, 1986). We now analyze more closely three alternative approaches to creating knowledge and transferring information in product design and component development processes: "traditional" sequential development, overlapping problem solving, and modular product development.

"Traditional" sequential development processes

The "traditional" model of product design and development follows a sequential staging of design and development tasks (Takeuchi and Nonaka, 1986), as suggested in figure 11.2(a). In this model, after defining the product concept, design and development tasks are sequenced so that technology and component development tasks with the greatest need for new knowledge and with the greatest impact on other component design and development tasks are undertaken first. As the firm develops new technical knowledge about components and their interactions at each stage, it makes component design decisions and communicates new information about component interface specifications that allow the next stage of component design and development tasks to proceed. This process is repeated at each stage of development until all components and their interfaces are fully specified. Thus, a critical feature of the sequential development process is that the information structure of component interface specifications – i.e., the new product architecture – is the *output* of the design and development process.

Recent research has made evident the likelihood of breakdowns, losses, and delays in information flows when product development processes are organized as a sequence of development tasks (e.g., Clark and Wheelwright, 1993). A sequential ordering of design and development tasks, for example, typically results in recursive information flows that often slow the development process, as suggested by the information feedback flows in figure 11.2(a). A sequential process is also likely to "lose information" as development proceeds from one stage to the next, because

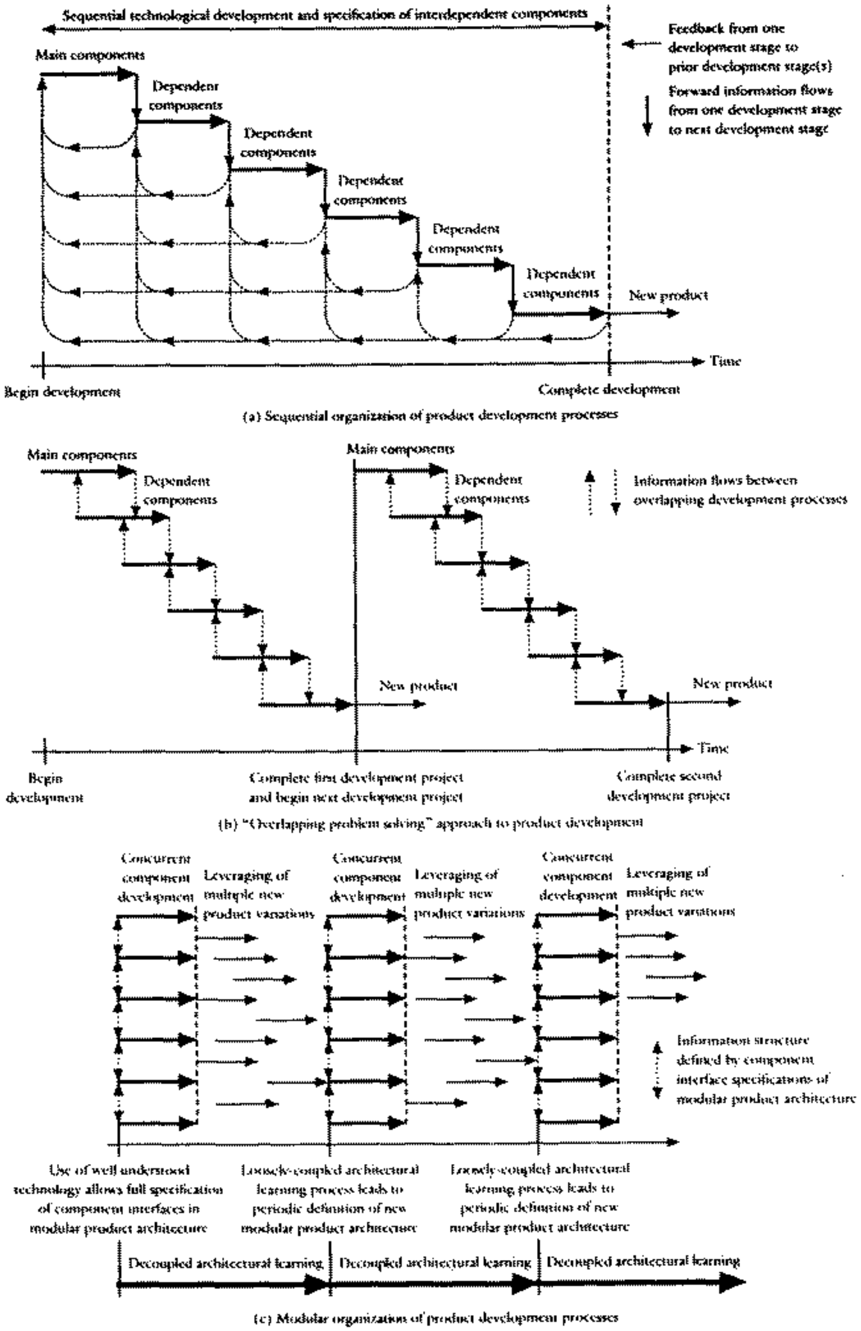

Figure 11.2 (a) "Traditional" sequential organization of product development processes (b) "Overlapping problem solving" approach to product development (c) "Modular" organization of product development processes.

the information and assumptions underlying upstream design decisions may not be transferred intact to downstream stages of development. Technical incompatibilities between interdependent components may then actually be "designed into" downstream components.

We suggest here that in addition to these well-known effects, the incomplete information structure of an *evolving* product architecture also has profound implications for feasible approaches to organizing this kind of development process. Because the information structure of an evolving product architecture is incomplete and indefinite until all stages of component development are completed, the desired outputs of specific component development tasks cannot be fully specified before beginning development. Coordinating incompletely specified but interdependent development tasks will require managerial adjudication of many technical and financial issues likely to arise between component development groups. The authority hierarchy needed to manage a sequential development process requires, in effect, the *tightly coupled organization structure* of a single firm or a firm with strong ties to a "quasi-integrated" group of dependent component suppliers (Nishiguchi, 1994; Sanchez, 1995).[7]

Overlapping problem solving

An alternative model for managing product development organizes the sequential development processes of figure 11.2(a) into staggered but overlapping stages, as shown in figure 11.2(b). Overlapping development stages make possible greater sharing of current information through processes of *overlapping problem solving* (Clark and Fujimoto, 1991; Clark and Wheelwright, 1993) that link closely interrelated component design and development tasks. Overlapping problem solving, which is often carried out in a team-based organizational structure (Takeuchi and Nonaka, 1986), improves information flows between overlapping development tasks, as suggested by the information feedbacks in figure 11.2(b), allowing some interrelated component development to proceed more quickly and reducing information losses between stages.

Although it offers improvements over a sequential development process, an overlapping problem solving process also has an evolving information structure (i.e., product architecture) and thus also requires intensive managerial coordination of incompletely specified development tasks within the boundaries of a single firm or within a small group of quasi-integrated component developers. Clark and Fujimoto (1991), for example, have observed that development projects using overlapping problem solving are more successful when they are managed by a "heavyweight project manager" who has the *authority* to make design and specification decisions and adjudicate disputes between development groups.

Modular product design

Modular product design follows a new model for managing learning and knowledge in product creation processes. In contrast to the evolving information structures characteristic of the sequential and overlapping problem solving models, a modular product design process creates a complete information structure – i.e., the fully specified component interfaces of a modular product architecture – that defines required outputs of component development processes *before* beginning development of components. To fully specify component interfaces in a modular product architecture, a firm must have, or have access to, advanced *architectural* knowledge about relevant components and their interactions.

When a firm can use advanced architectural knowledge to specify a new modular architecture within which development of modular components can take place, learning at the modular or incremental levels through developing new and improved components may be improved by being *intentionally separated* from and made only *loosely coupled* to processes for creating new architectural knowledge. Moreover, processes for learning at both levels may become more efficient.

Improved component-level learning

When learning through the development of individual components can take place within the stable information structure of a fully specified product architecture, learning inefficiencies due to breakdowns, losses, and delays in information flows between component development activities can be avoided. In effect, adopting a modular design process allows learning at the component level to be "insulated" from disruptions by unexpected changes in product architecture during development projects.

Because fully specified component interfaces allow component-level learning processes to be carried out *concurrently and autonomously* by geographically dispersed, loosely coupled development groups, as suggested in figure 11.2(c), a firm may be able to combine its capabilities more readily with those of an extensive network of component developers, thereby increasing the absorptive capacity of the firm (Cohen and Levinthal, 1990) and its potential for realizing the full *combinative capabilities* (Bartlett, 1993; Kogut and Zander, 1992) of the firm's current architectural knowledge. Decoupling architectural and component levels of learning may therefore allow a firm to be more effective in exploiting its current stock of architectural knowledge (March, 1991). After the initial round of concurrent component development suggested in figure 11.2(c), a developing firm may use the stability of a modular product architecture to accelerate network-based development of new kinds of "mix and match" modular components for leveraging product variations.

A modular product design process may therefore enable a firm to accelerate its *learning about markets* by enabling the firm to leverage many different variations of a product more quickly and at reduced cost. In effect, allowing more focused component-level learning within a current product architecture may facilitate an evolutionary process of real-time market research (Sanchez and Sudharshan, 1993) that supports accelerated creation of market knowledge in an enterprise (Baldwin and Clark, 1994). The decoupling of architectural and component learning processes may also create a more efficient environment for involving suppliers and customers in "localized learning" in developing specific components. Boeing's use of a modular design process in developing the 777 aircraft (Woolsey, 1994), for example, created a decoupled component-level learning environment that facilitated the involvement of Boeing's lead customers in developing improved designs for key components which directly affect customers' use of the 777. Use of modular product architectures to achieve a managed separation of architectural and component learning may therefore provide a framework that supports expanded involvement of lead users (von Hippel, 1988) in product development.

Improved architectural-level learning

The loose coupling of learning at the component and architectural levels may also improve architectural learning processes. Henderson and Clark (1990) suggest that organizations tend to lose their abilities to innovate at the architectural level, because over time organizations develop organizational structures and information channels that are focused on component-level activities. Compartmentalization of organizations and information around components creates "filters" that block flows of information that would suggest opportunities for architectural innovation. A further set of concerns about architectural learning arises from the "project" nature of most product development processes. The time-sensitive, high-pressure environment which often characterizes new product development projects is likely to impose severe constraints on the time and resources which can be devoted to learning at the "architectural" level. Using specific product development projects as the *context* for creating new technical knowledge may therefore lead to an excessive focus on incremental (and perhaps modular) learning which can be applied immediately to current development needs. Learning at the architectural level, when intentionally decoupled from learning at the component level, may become more open to technological and market change, less dominated by the near-term demands of component-level learning during development projects, and thus less suceptible to falling into patterns of myopic learning (Levinthal and March, 1993).

Using modular product architectures as mechanisms for coordinating organizational learning

The process of periodically revising or creating a new modular product architecture provides an important coordinating mechanism for periodically linking loosely coupled processes for learning at architectural and component levels. Learning at the architectural level may suggest advantageous changes in components compatible with a current product architecture (i.e., opportunities for modular learning), as well as possibilities for significant changes in both components and product architectures (opportunities for radical innovations). Periodic redefinitions of modular product architectures may therefore provide a "programmed" opportunity for reconnecting and coordinating architectural and component-level learning.

The shifting focus of knowledge management in modular product development

Modularity in product designs and organization designs for developing products may lead to a fundamental shift in the nature and focus of strategic learning activities in firms. Firms that create new products through modular product development are likely to place increasing emphasis on learning at the architectural level, while focusing and intensifying component-level learning in one or a few key components of subsystems that are critical to overall product performance and in which a firm possesses superior development capabilities.

Examples of this new pattern of "modular learning" can be found in a growing number of industries, from high-tech to industrial. As an example of the latter, we cite Venkatesan's (1992) analysis of product competition in the earth-moving equipment industry. Venkatesan (1992) discusses the product architecture of a backhoe/loader – a complex mechanical system composed of a number of subsystems of components such as hydraulics, drive train, chassis, ground-engaging tools, vehicle electronics, operator cab, and engine. Venkatesan (1992: 101–103) describes the process of deciding which components and subsystems will become the focus of a firm's own learning efforts and which the firm will manage by using its architectural knowledge to define modular component interface specifications:

> The first thing to decide is what subsystems will be indispensable to the company's competitive position over subsequent product generations. This choice will vary from company to company and ultimately drive product differentiation. . . . [W]hen capable subsystem suppliers exist, it is not so important to be able to design and manufacture the sub-system in-house as it is to have *the ability to specify and control the performance characteristics of the subsystem.* [italics added for emphasis]

Venkatesan's (1992) observations suggest that much strategic learning is now directed at improving a firm's architectural knowledge needed to control the specifications of subsystems and components in a modular product architecture. This kind of architectural learning is becoming a strategically important means for assessing and coordinating an extended network of component development capabilities in other organizations (Sanchez, 1996d; Sanchez and Heene, 1996). As more firms begin to use modularity not just to create greater product variety, but also as a new framework for aggressive strategic learning and more effective knowledge management, new innovation dynamics are being created whose implications for technology-driven competition invite further investigation.

Conclusions

A useful tool for management and organization science is to make use of the world's redundancy to describe the complexity of our world as simply as possible (Simon, 1981: 222). The principle of the decomposability of systems deepens our understanding of the architecture of complexity, whether the system in question is physical, biological, social, or economic. Our effort to understand more fully the potential for *intentionally decomposing* complex products and organizational phenomena into loosely coupled subsystems suggests an approach to gaining new insights into the structure and dynamics of changing product markets and evolving organizational forms.

Extending the principle of decomposition, this paper has suggested that the creation of modular product architectures not only creates flexible product designs, but also enables the design of loosely coupled, flexible, "modular" organization structures. Embedding coordination in fully specified and standardized component interfaces can reduce the need for much overt exercise of managerial authority across the interfaces of organizational units developing components, thereby reducing the intensity and complexity of a firm's managerial task in product development and giving it greater flexibility to take on a larger number and/or greater variety of product creation projects.

Adam Smith (1776) showed early insight into the importance of managing knowledge by suggesting that a firm organized around processes based on the specialized *content* of knowledge may gain efficiencies in producing physical products. Here we make an analogous argument about knowledge-intensive work: organizing a firm around specialized *processes for creating and applying* knowledge can lead to important dynamic efficiencies in the production of *intellectual* products in the form of new product and component designs and technologies.

We expect that the knowledge management processes of product-creating firms pursuing greater dynamic efficiencies will become increasingly focused on the codification of architectural knowledge about component interactions needed to specify modular product architectures and on using that architectural knowledge to coordinate loosely coupled modular organization structures for component and product development. In general, while firms may develop specialized knowledge about some strategically important modular components, we expect firms to undertake internal development of fewer components, as more product-creating firms learn how to use modular architectures to source more components through loosely coupled networks of component suppliers. Growing strategic use of modularity as a framework for more effective strategic learning and knowledge management may result in increasingly dynamic product markets. These are likely to be characterized by expanding interactions among modular development organizations through "quick-connect" global electronic networks (Sanchez, 1996a). The consequences of this new modular creation environment will be previously unattained levels of product variety and change.

Discontinuities in product technology (Tushman and Anderson, 1986) lead to changes in the *content* of product markets – i.e., to new kinds of products made by new organizations. This paper, however, has described the rise of modular product design as a recent discontinuity in *coordination technology* (Sanchez, 1996b) that is leading to changes in the *processes and structures* of product markets – i.e., to new kinds of product development processes carried out by new forms of product development organizations. Thus, the possibilities for adapting new coordinating technologies and knowledge management processes based on modularity concepts are making it possible as never before for *organizational form* to become a variable to be managed strategically.

Finally, this paper concludes that the increased flexibilities that can result from the embedded coordination of standardized interfaces in modular architectures may not be limited to product development processes. The flexibilities to be derived from the standardized interfaces of modular architectures also appear to be attainable in the design of marketing, distribution, and other processes. Thus, we suggest that standardizing interfaces in modular system architectures of many types may be a new dominant design for achieving increased flexibility and interorganizational connectivity among broadly de-integrating organizations.[8]

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NOTES

Key words: coordination; knowledge management; modularity; strategic flexibility.

1 Product design should be recognized as a strategic activity with important economic implications. A 1986 study at Rolls-Royce suggested that design determines 80 per cent of the final production costs of 2000 components, and General Motors executives maintain that 70 percent of the total cost of manufacturing truck transmissions is determined in the design stage (Whitney, 1988).

2 In fact, Radner (1992: 1392) poses the question "Would a hierarchical design of the processes of production [necessarily] lead to hierarchical management?" In effect, what we are suggesting in this paper is that specific forms of hierarchical designs of processes *need not* be accompanied by hierarchical management.

3 Note that tight or loose coupling of components in a product *design* is different from tight or loose coupling in an actual (usually physical) product. A personal computer design, for example, may have loosely coupled components in that different microprocessors or hard disk drives may be substituted into the computer design without requiring a redesign of the other components. Nevertheless, the components in the physical computer will be tightly coupled in the sense that all components must function properly for the computer to function as a system.

4 Specifying standardized interfaces to create loosely coupled components allows each component within a product design to be treated as a "black box" (Wheelwright and Clark, 1992) by the product developing firm. In developing new car models, many car makers now provide their suppliers with only a "black box" specification of the (standardized) functional, spatial, and other interfaces of the required component, leaving the actual design and development of the component to the supplier (Clark and Fujimoto, 1991). This design principle is also evident in software development, where object-oriented programming methods require that each component of a program be written by software developers who have no knowledge of the code used by other developers in writing their program components. Decomposition of program design allows a regime of "information hiding" among program component developers (Parnas, 1972) analogous to "black box" component development in the automobile industry. (For further discussion of standards and interfaces, see David and Greenstein, 1990.)

5 Shirley (1990) investigates the potential for product designs using modular components to provide a large number of product variations while reducing overall manufacturing costs. We suggest that modularity in product design creates many options for product variations in the form of feasible combinations of modular components, some of which may be drawn from a "design library" of existing components. In this regard, leveraging product variations from modular designs is a specific expression of Kogut and Zander's (1992) "combinative capabilities" in the context of creating new products.

6 In a more general sense, embedded coordination is the coordination of organizational processes achieved by any means other than the continuous exercise of managerial authority and may include, for example, clan coordination through tradition (Ouchi, 1980). We thank the editors for bringing this point to our attention.

7 A further argument for the necessity of carrying out sequential development processes within a single firm is the difficulty of contracting for component development services when the *performance* of a contractor would be difficult to assess, given the high degree of dependence of each development group's work on the effort of other development groups (Alchian and Demsetz, 1972; Ouchi, 1980).

8 We observe, for example, that modularity in product designs can facilitate modularity in manufacturing processes as well as in development processes. In industries whose product designs are typically most modularized (e.g., personal computers), production, assembly, and servicing of components are commonly carried out by globally dispersed, loosely coupled organizations.

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Commentary

Ron Sanchez

Introduction

The 1996 *Strategic Management Journal* paper co-authored with Joe Mahoney and reprinted in this volume undertook to lay out a broad yet fundamental view of how modular product architectures can impact product creation processes, market strategies, organization designs, competitive dynamics, and industry structures. The paper also suggested some ways in which modular architectures could provide a new framework for learning and knowledge management processes within firms and industries. Some of the modularity concepts presented in the paper were greeted with considerable skepticism or incomprehension at the time.[1] I am happy to be able to say now that modularity concepts are becoming better understood and increasingly accepted in both management practice and academia.

In this retrospective appraisal of the paper, I summarize what I believe are the main ideas contributed by the paper, discuss Herbert Simon's important influence on those ideas, and identify what I believe are some of the more interesting and significant extensions of modularity ideas developed since 1996. In this discussion, I suggest some connections of modularity concepts to standards, networks, complexity, co-evolution of technological and social systems, and other concepts developed in some of the papers reprinted in this volume. I conclude with comments on the enabling role of modular architectures in eBusiness.

The main ideas about modularity

In essence, the *Strategic Management Journal* paper makes the following arguments:

- Modular architectures are product designs that are strategically conceived as "platforms" for substituting (Garud and Kumaraswamy, 1993) a range of component variations in order to configure a range of product variations. The key to "designing in" substitutability of components is the specification and standardization (David, 1987) of interfaces between components to allow the "mixing and matching" (Sanderson and Uzumeri, 1990) of component variations in the modular architecture. The range of component variations which the interfaces in an architecture can accommodate determines the *flexibility* of the architecture to configure new product variations, which in turn greatly affects the *strategic flexibility*[2] of a firm to respond to changing market demands in the near term (Sanchez, 1995).
- The standardization of interfaces that support substitutability of component variations enables component development processes to become loosely coupled (Weick, 1976). Loose coupling of development processes results because the standardization of interfaces creates, in effect, a stable technical infrastructure for the product type. A stable technical infrastructure provides a well-defined information structure that specifies how the component parts of the product as a system function together. As long as all component development groups develop components that conform to the standardized interfaces, the decisions made by one development group do not affect other groups' development processes. Product development processes can then be coordinated through the information structure of standardized interface specifications, avoiding the need for authority-based hierarchical coordination (Mahoney, 1992). Thus, standardized interfaces may make it possible for a firm to adopt a "modular" development process that draws on the resources of networks of component developers around the globe (Langlois and Robertson, 1992). Using the standardized interfaces of a modular architecture to coordinate a modular development organization is one instance of the general proposition made in the paper that *products design organizations*. In essence, the way a firm decomposes and interrelates the components in its product designs will greatly affect the organization designs a firm can adopt for developing, producing, and supporting its products.
- To specify component interfaces that allow substitutability of component variations, a firm must have high levels of architectural knowledge – that is, knowledge about how components interact in a product as a system. Architectural knowledge used to specify interfaces between components can be distinguished from component-level knowledge that enables a firm to design a given type of component.[3] In conventional development processes (see figure 11.2(a) in the 1996 paper), the component designs and interfaces in a product design are co-evolving and complexly interdependent, and architectural and component forms of knowledge are thus tightly coupled. In modular development processes, however, interfaces are specified and standardized before beginning component development processes, and component designs are constrained to conform to

the standardized interface specifications (see figure 11.2(c) in the paper). The standardizing of component interfaces based on the firm's current architectural knowledge largely decouples architectural knowledge-based processes from the component-level knowledge used to develop specific component designs during product development. This decoupling of architectural and component-level knowledge during product development greatly reduces the complexity of the learning environment during development and can therefore increase the efficiency with which current architectural and component-level knowledge can be applied and new knowledge of both types generated.

Herbert Simon's influence

The initial impetus for the 1996 paper was my research into using modular product architectures as platforms that give firms strategic options to leverage a range of new product variations quickly and inexpensively (Sanchez, 1991, 1993, 1995). As Joe Mahoney and I discussed modularity concepts, however, it became clear to us that an architecture essentially referred to a well decomposed and specified system, and in particular that modular architectures had many of the properties that Herbert Simon (1962) had attributed to "nearly decomposable systems." Simon's paper *The Architecture of Complexity* suggested a fundamental connection between our ideas about modular architectures and Simon's ideas about nearly decomposable systems.

The key connection was the shared concept of ***decomposability***. Simon proposed that hierarchy is an organizing principle of nature, which he clearly saw as consisting of systems that cover the spectrum from the subatomic to the galactic, from the elegantly simple to the enormously complex. In Simon's structural conception of hierarchy, decomposition represents a partitioning of a system into interacting subsystems, of subsystems into sub-subsystems, and so on, down to the most elemental building blocks of a system. A "nearly decomposable system" is the term Simon used to refer to a system in which the interactions among subsystems are relatively weak compared to the interactions between the parts within subsystems.

Because the first step in creating an architecture is the decomposition of a product or process design into interacting functional components, an architecture represents a hierarchical ordering of parts through decomposition, as described by Simon. Moreover, a modular architecture is a ***design*** that intentionally creates weak interactions between component designs in order to allow the substitution of component design variations into the architecture. Thus, a modular architecture has the essential distinguishing property of Simon's nearly decomposable systems.

Simon observed that nearly decomposable systems often demonstrate high levels of adaptability. Because of the weak interactions between subsystems in a nearly decomposable design, it may be possible for one part of a nearly decomposable system to change without having to make changes in other parts of the system – thereby increasing the adaptive capability or evolvability of the system. Analogously, improved adaptability of product designs through substitution of new component design variations is also an important benefit sought through modular architectures.

Although these basic similarities are important, there is also a noteworthy difference between Simon's concept of nearly decomposable systems and the concept of modular architectures. These differences no doubt arise from the different perspectives from which Simon on the one hand and Joe Mahoney and I on the other approached the study of systems. Simon's perspective was essentially that of the natural scientist interested in describing and explaining nature as he saw it, and the outcome of such a process is descriptive, positive scientific theory. Joe Mahoney and I approached the study of modularity primarily as management researchers interested in devising better strategies for managing human systems, and the outcome of our investigation was intended to be new prescriptive (normative) management theory. Thus, an essential differentiator between the two perspectives is that Simon's concept of near decomposability may describe all kinds of natural systems, while the concept of modular architectures applies to product or process system designs that are motivated by a ***strategic intention*** to create more adaptable products and processes and thereby improve the strategic flexibility of an organization. In the hierarchical ordering of concepts, therefore, modular architectures are a subset of nearly decomposable systems – but a subset of central importance to management theory and strategy.

Important extensions of modularity concepts

My research to date has largely confirmed the key propositions about modularity made in the 1996 *Strategic Management Journal* paper. For example, the paper suggests that specifying and standardizing interfaces in modular product development allows parallel, concurrent development of components, and that concurrent development of components should greatly reduce both time and resource requirements for developing new products compared to conventional development processes (compare figure 11.2(c) to 11.2(a) in the 1996 paper). Evidence gathered from a growing number of companies suggests that this modular process for developing products can in fact reduce development costs, resource requirements, and time to market by 50–80 percent compared to conventional development processes (Sanchez, forthcoming). Moreover, the reduced complexity that results from the decoupling of architectural and component-level knowledge in modular development processes can indeed significantly improve both the efficiency and effectiveness of organizational learning and knowledge leveraging (Sanchez and Collins, forthcoming).

Further, my research has progressively led to the view that modularity concepts are not just relevant for product and process designs, but rather suggest fundamentally important new conceptions of organization and management (Sanchez, 1997 and forthcoming; Schilling, 2000). Today I propose that modularity should be seen as a fundamental approach to organizing and managing, not just as a strategy for designing products. The logic behind this more extensive view took a while to come into clear focus, but now seems quite evident: modularity is essentially a way of designing systems to be more adaptable, and both organizations as systems and management processes as systems can therefore be made more adaptable by adopting modular system designs. In addition, my research has also suggested strongly that achieving the full benefits of modularity in product strategies requires extending modularity practices to many interrelated activities in an organization. Following are three of the key aspects of this subsequent, more extensive view of modularity.

Modularity in the marketing processes

Modular product architectures can enable firms to offer more product variations more frequently and at lower costs. As noted in the 1996 paper, this flexibility of modular architectures makes it possible to learn about markets through *real-time market research* – a process of introducing a changing array of new product variations to discover which combinations of functions, features, and performance levels the market will prefer at various price points (Sanchez and Sudharshan, 1993). However, the flexibility of modular architectures also makes it possible to probe markets more widely and more finely. Both new capabilities have significant implications for the marketing process (Sanchez, 1999).

Traditional marketing is essentially concerned with discovering convergence (means) in the distributions of demand for different products in order to identify the attributes of products for which demand is most likely to be significant. The time-consuming and often costly methods of traditional marketing research may become quite problematic to use when market preferences are diverse and evolving rapidly. When many product variations can be leveraged from a modular architecture, however, an alternative mission for marketing research is discovering the evolving divergence (variance) in demand that might be served through a highly configurable modular architecture. In essence, much of the risk inherent in defining new products to serve diverse and evolving consumer preferences may be managed more satisfactorily through the flexibility of well-conceived modular product architectures than through traditional marketing research methods.

Modularity also challenges the central concept of market segmentation in marketing theory and practice. Market segmentation has been a foundational concept in marketing theory and practice for so long that the reasons behind the concept of segmentation are often overlooked. In essence, consumers have been grouped into market segments because the cost of creating products for individual consumers has been assumed to be prohibitive. Modular architectures, however, make it possible to segment markets much more finely than ever before – even to the level of mass-customized or personalized products for individual consumers. When a firm develops a modularity-based mass-customization capability, the usual marketing assumption about the prohibitive cost of serving individual customer preferences no longer holds. Once a product market starts to "go modular," the marketing process becomes much more concerned with defining menus of component variations to offer to individual customers than with grouping of customers into traditional market segments to be served by specific differentiated products.

Modularity in knowledge management

Modular architectures can greatly improve an organization's ability to identify and leverage its current knowledge and to identify opportunities for strategically important organizational learning (Sanchez and Collins, forthcoming). A firm's knowledge becomes embodied in specific components of its products and processes and in the firm's processes for coordinating those components in its products and processes as systems. Firms that develop products in the modular way usually develop "design libraries" of available modular component designs that can be used in their existing architectures. The component designs that a firm has in its design library represent an inventory of the readily available intellectual assets (component designs) that can be used immediately to configure new product variations. A firm that creates a design library of available product and process components can begin to see more clearly its current capabilities to configure new products in the short run – in effect, it begins to "know what it knows how to do" better than firms that do not systematically define and catalog available component designs. When new product opportunities come along that would require new component designs, the lack of suitable component designs in the design library helps a firm to understand its current capability limitations – in effect, to "know what it does *not* know how to do" in the short run. A firm may then focus its organizational learning on developing appropriate new component designs to meet new product opportunities. In this way, modular architectures provide a framework that helps a firm discover and focus on opportunities for strategically important organizational learning and capability development.

The adoption of standardized component interfaces within a firm or an industry also creates a stable technical infrastructure (for some period of time) for a given type of product architecture (for example, the "Wintel" personal computer architecture). A stable technical infrastructure gives rise to a socio-technical system that is populated by people who develop architectural or component level knowledge about the product architecture – in effect, forming a "community of practice" based on the architecture (Wade, 1995). Firms may then define their own modular architectures to be consistent (either partially or entirely) with the prevailing industry interface standards. Adopting industry standard interfaces makes it possible for a firm to invite the participation of external component developers and producers in its own product creation and realization processes, because those developers already have expertise in the technical system requirements of such components. Thus, adopting modular architectures that incorporate industry standard interface specifications is a critical step in strategies for accessing a world of external expertise that can improve a firm's own product creation and realization capabilities (Sanchez, 2000a, 2000b).

Modularity in competence-based strategic management

The competence-based perspective on strategic management is concerned with devising new management theory and practice that incorporates essential dynamic, systemic, cognitive, and holistic dimensions of the management task (Heene and Sanchez, 1997; Mahoney and Sanchez, 1997; Sanchez, 2001). Modularity brings important new possibilities to the advancement of competence-based management in several of these dimensions.

The dynamic challenge in managing arises from the ongoing changes in both market preferences for products and the technological means for creating new products. The configurability of modular architectures can make it possible for a firm to rapidly change or upgrade its products by substituting new, higher performing component variations into its product architectures – thereby improving the ability of the firm to respond to market and technology dynamics.

The systemic dimension involves managing change in an organization as a system. When organizations are composed of units that interact in inflexible, idiosyncratic ways, change processes become very complex, and managers can have great difficulty in realigning organizations with changing market and technology conditions. The concept of modular architectures, however, can be applied to process designs as well as product designs to create more configurable, evolvable organization designs. An organization's processes becomes modular when they are decomposed into intentionally loosely-coupled activities that interact in standardized ways – that is, through standardized process interfaces. When various internal and external organization units understand the standardized process interfaces of the organization (and have adequate incentives to work within that structure), those units may be substituted into the organization's process architecture to configure variations in the organization's chain of resources that can help the organization respond to changing environmental conditions. In this respect, standardizing an organization's activity interfaces is as essential to outsourcing manufacturing, distribution, and support activities as standardizing product component interfaces is to outsourcing component development (Sanchez, 2000b).

The modularity perspective also provides both conceptual arguments and empirical evidence against the proposition that the resource endowments of firms alone can adequately explain the differential performances of firms – a central tenet of the resource-based view in strategy theory (Barney, 1986, 1991). Modularity is a new way of *coordinating* resources in the creation and realization of products. The same development resources coordinated through conventional or modular development processes can have very different levels of productivity and market impacts. Thus, any strategy theory that aspires to explain differential performance in product creation, for example, must look not just to the development resources within a firm, but to the ability of the firm to coordinate its development resources in the most effective way.

The cognitive challenge in managing derives from the increasing complexity of modern organizations and their environments. Managers need frameworks that can help them to adequately conceptualize essential processes and capabilities in their organizations and the changes that both must undergo for an organization to remain competitive. Many firms today, for example, do both market and technology forecasting in an effort to conceptualize future market conditions and technology possibilities. Interpreting such forecasts to define specific objectives for the future is likely to remain problematic, however, without a framework for integrating technology and market trends to define a plan of action. As platforms for using available technologies to serve emerging market needs, modular architectures offer a useful and perhaps essential framework for defining the new kinds of products that will be both possible and desirable in the future, for defining the new kinds of components that will be needed in those products, and the new architectural and component-level capabilities a firm will need to create and realize its future generation product architectures. In some firms today, the definition of future generation modular architectures and the capabilities that will be needed to create and realize those architectures has become the driver of long-term product strategies and strategic

capability development processes (Sanchez, 2000a, forthcoming; Sanchez and Collins, forthcoming).

Modularity in eBusiness

The 1996 paper suggested that increasing adoption of modular architectures would result in more dynamic product markets "characterized by expanding interactions among modular development organizations through 'quick-connect' global electronic networks." The rise of internet-mediated eBusiness has brought the era of "quick-connect" global eBusiness relationships into existence, and modular architectures are the foundation for both the *process* and the *content* of eBusiness.

The Internet itself is a modular communication architecture with well defined and standardized interfaces for "quick-connecting" computer systems around the world. The flexible, "platform-independent" interfaces of the internet make it possible for any company with a computer equipped with a browser to "plug and play" in the global internet communication architecture. Of course, connected buyers must still find the right connected suppliers, and vice versa. On the B2B (business to business) side, a large number of both general and industry-specific electronic marketplaces are now emerging to provide meeting places for buyers and suppliers. Within the industry marketplaces, modularity concepts are prominent in the standardized processes through which buyers and suppliers interact in eBusiness platforms. The automobile industry eBusiness marketplaces, for example, require that interested suppliers submit offers to provide components through standardized process interfaces – that is, standard document formats that allow consistent electronic data integration (EDI) and dissemination to interested buyers throughout the industry. Thus, the B2B eBusiness platforms being put in place today are effectively creating modular process architectures for managing the information content and coordination of buyer-supplier interactions globally. On the content dimension, B2B platforms are also encouraging greater standardization of component interfaces and even component designs. Because a firm cannot readily contract for a component development or production services if the technical specifications of the component are not fully determined, companies now have significant new incentives to fully specify and standardize their component interfaces in order to use eBusiness marketplaces to invite offers to supply components from the global pool of connected component suppliers.

On the B2C (business to consumer) side, modular architectures play an even more visible role. The mass-customization and personalization[4] of products for individual customers virtually requires the use of flexible modular product architectures to configure individual product variations for individual customers. Moreover, as more consumers around the world choose their preferred combinations of components for mass-customized or personalized products, firms offering such products must expand the resources they can access to provide both new product component variations and new process component variations (assembly, shipping, and support services). Thus, behind the growing use of modular architectures to configure product variations for individual customers is the increasing creation of modular supply chains to provide new modular component variations and to assemble, ship, and service specific product variations (Sanchez, forthcoming).

As eBusiness becomes more widely adopted as a standard business process on both the B2B and B2C sides, considerable new incentives are being created for firms to adopt standardized components for both their product and process architectures. As more firms adopt modular architectures to serve demand for mass-customized and personalized products and to standardize product and process components and interfaces to coordinate global supply chains, more eBusiness processes are beginning to grow and to become important new marketplaces for firms that are "modular capable." Thus, today a powerful new "virtuous circle" driven by the benefits of increasing modularity and connectivity is taking shape in the global business environment. The dynamic of this virtuous circle is setting the stage for the next chapter in the evolution of modularity concepts.

NOTES

1 A version of the 1996 paper was rejected by the journal *Organization Science* in 1995. In her rejection letter, the area editor characterized the paper as presenting "a naive view of product development."

2 The strategic flexibility of a firm can be represented as the sum of the *strategic options* available to a firm to introduce new product variations. Strategic flexibility increases with the number of (positive net present value) strategic options a firm has, and decreases with the time and cost required to exercise each strategic option (Sanchez, 1993, 1995).

3 Of course, for a component supplier, the component is its product, and the component maker must have architectural knowledge about how its component functions as a system. Architectural knowledge at the component level can then be distinguished from knowledge about how the individual subassemblies or parts within the component must be designed. Thus, in a fundamental sense, ***architectural knowledge is knowledge about how the parts of a system function together***, whether the system be at the level of a component, a product, or the macro-system that defines the context of use of a product.

4 Mass-customization configures individual product variations from a menu of standard component variations. Product personalization configures individual products that include at least one component that is made specifically to suit an individual customer's requirements (Sanchez, 1999). Products like personal computers are commonly mass-customized, while articles of clothing and footwear typically are increasingly available offered as personalized products that conform exactly to a an individual's body measurements.

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To the memory of Herbert A. Simon

"How complex or simple a structure is depends critically upon the way in which we describe it."

Simon, 1962

MANAGING IN THE MODULAR AGE

ARCHITECTURES, NETWORKS, AND ORGANIZATIONS

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