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

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This paper investigates interrelationships of product design, organization design, processes for learning and managing knowledge, and competitive strategy. This paper uses the principles of nearly decomposable systems to investigate the ability of standardized interfaces between components in a product design to embed coordination *of product development processes. Embedded coordination creates 'hierarchical coordination' without the need to continually exercise authority—enabling effective coordination of processes without the tight coupling of organizational structures. We develop concepts of* modularity *in product and organization designs based on standardized component and organization interfaces. Modular product architectures create* information structures *that provide the 'glue' that holds together the loosely coupled parts of a modular organization design. By facilitating loose coupling, modularity can also reduce the cost and difficulty of adaptive coordination, thereby increasing the* strategic flexibility *of firms to respond to environmental change. Modularity in product and organization designs therefore enables a new strategic approach to the* management of knowledge *based on an intentional, carefully managed* loose coupling *of a firm's learning processes at architectural and component levels of product creation processes.*

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 devel-

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opment 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

[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.

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]

[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,

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 specifications 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 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).

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]

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.

Table 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 truck 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)

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 1 identifies four modes of learning—radical, architectural, modular, and incremental—that can occur in product innovation processes (cf. Henderson and Clark, 1990).

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 of 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 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

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 1. Modes of learning in product creation processes

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 2(a). A sequential process is also likely to 'lose information' as development proceeds from one stage to the next, because 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]

[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

Overlapping problem solving

An alternative model for managing product development organizes the sequential development processes of Figure 2(a) into staggered but overlapping stages, as shown in Figure 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 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 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 2(c), a developing firm may use the stability of a modular product architecture to accelerate network-based development of new kinds of 'mix

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).

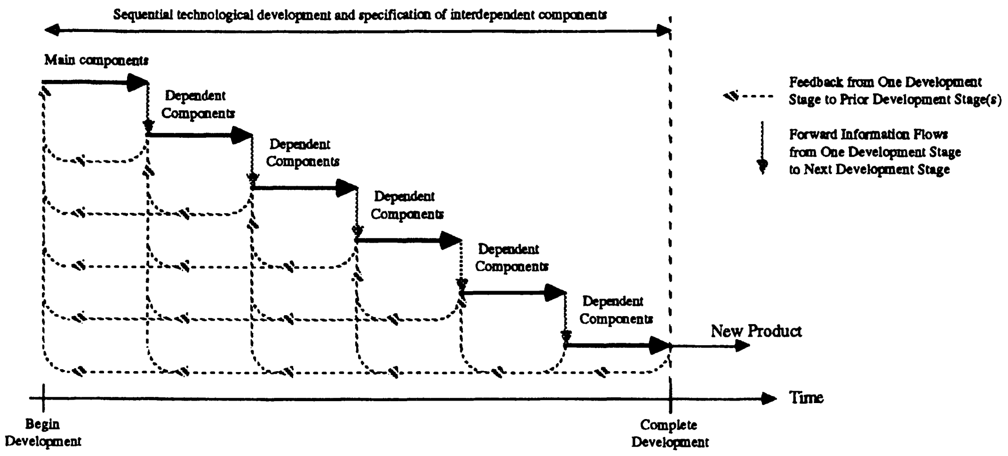

Figure 2(a): Sequential Organization of Product Development Processes

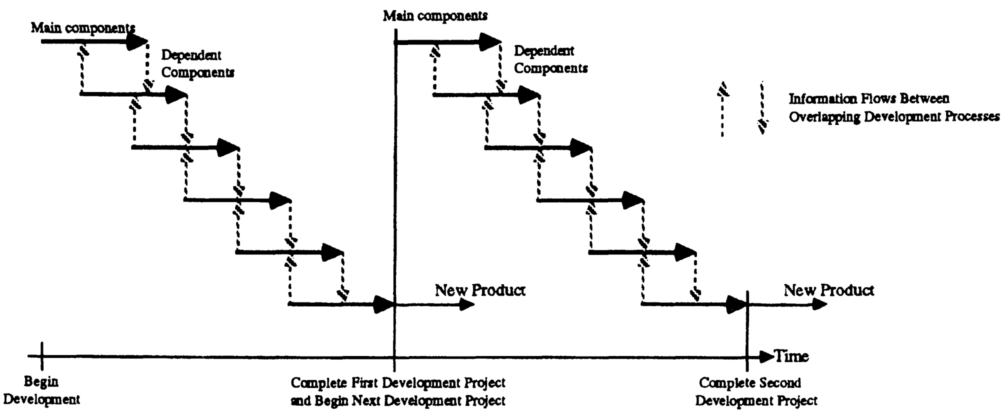

Figure 2(b): "Overlapping Problem Solving" Approach to Product Development

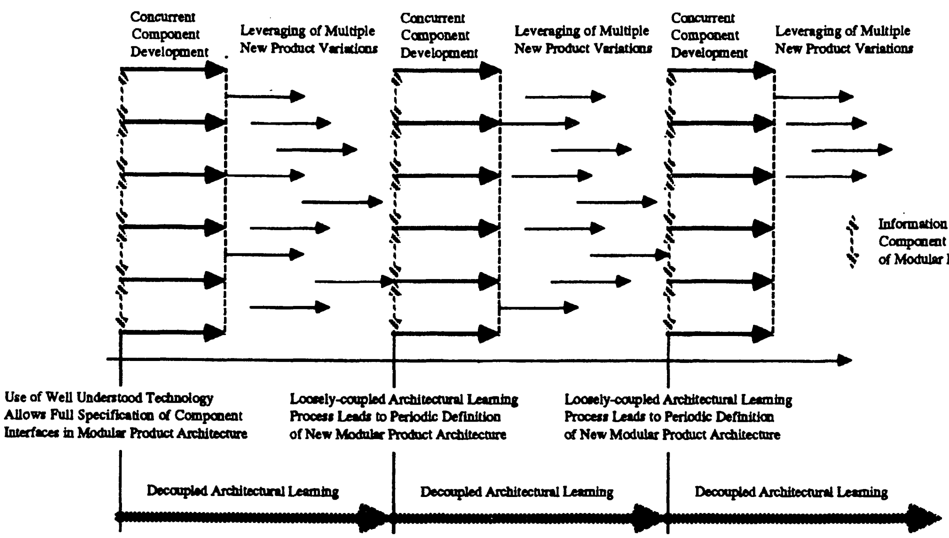

Figure 2(c): Modular Organization of Product Development Processes

Figure 2. (a) 'Traditional' sequential organization of product development processes (b) 'Overlapping problem solving' approach to product development (c) 'Modular' organization of product development processes

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]

[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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