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Modularity and Dynamic Capabilities

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In this chapter we explain how using modularity to create flexibilities in both product and organization designs (Sanchez, 1995a; Sanchez and Mahoney, 1996) can enhance dynamic capabilities development (Teece et al., 1997). We explain the concept of modularity in products and organizations, and we suggest ways in which modularity provides a framework for strategically managing learning processes that can be effective both in developing capabilities and applying capabilities to external market opportunities and requirements. In this manner, we suggest that modular product and organization designs provide a fundamental framework for improving the adaptive co-ordination of firms in dynamic environments.

The first step in creating modularity in product designs is standardizing input and output interfaces between the functional components that make up a product. Standardizing interfaces allows the decomposition of an overall product design into a nearly independent (Simon, 1962) or loosely coupled (Orton and Weick, 1990) system of functional components. Modularity in product designs is achieved when standardized interfaces between components are specified to allow for a range of component variations to be substituted into a product design without having to change designs of other components (Garud and Kumaraswamy, 1993).

The use of modularity in product designs may have important consequences for product market strategies, organization designs and organizational learning. The ability to substitute component variations into modular product designs increases the variety of products a firm can develop and the speed with which it can upgrade products, increasing the strategic flexibility of the firm in product market competition (Sanchez, 1991, 1993, 1995a). Decomposition of a product design into modular components also allows the autonomous and concurrent development of components by loosely coupled development organizations, making possible modular organization designs for creating and producing products (Sanchez and Mahoney, 1996). Modularity in product designs creates, in essence, a form of *embedded co-ordination* – hierarchical co-ordination that functions without continuous exercise of managerial authority – that lowers the cost and difficulty of organizing and managing complex processes. In ways that we explain below, modular product and organization designs provide a framework for more efficient technological learning processes both at architectural and component levels of technology (Sanchez, 1996a; Sanchez and Mahoney, 1996) and for accelerated market learning through processes such as real-time market research (Sanchez and Sudharshan, 1993). By reducing the costs, difficulty and required managerial co-ordination for developing and deploying new capabilities, modularity can improve the overall strategic flexibility of a firm to respond to and initiate strategic change at several levels within the organization.

Analogously, we suggest that standardized communication interfaces and procedural protocols of computer-assisted design and development (CADD), computer integrated manufacturing (CIM) and electronic data interchange (EDI) systems create 'quick-connect' capabilities between firms that further facilitate the modularization of organization structures and processes (Sanchez, 1996b). These quick-connect technologies may further extend the embedded co-ordination of modularity to include widely dispersed processes of technological and market learning in global networks of loosely coupled firms engaged in developing, producing, distributing and servicing products.

By improving a firm's own technology and market learning processes, and by extending the ability of a firm to co-ordinate and benefit from learning processes undertaken within networks of firms, modularity may provide a framework for improved and expanded organizational learning that reduces path-dependency effects in dynamic capabilities formation (Teece et al., 1997). We suggest that appropriate use of modularity may lead to improved capacities for learning in creating and applying know-how, know-why, and know-what forms of knowledge within organizations (Sanchez, 1996b, 1996c).

We also suggest that achieving improved strategic flexibility through modularity in product and organization designs enables a new conceptual fusion of intended (flexibility-building) and emergent (flexibility-deploying) strategies for managing the uncertainty of dynamic markets. The conceptual fusion of intended and emergent strategies through modularity concepts may constitute a fundamental and promising new approach to improving the integration and coherence of strategy formulation and implementation processes (Itami, 1987; Leonard-Barton, 1988, 1992; Mahoney, 1995) and thus to the more effective identification, building and leveraging of new capabilities on which a firm's ability to survive in dynamic environments ultimately depends.

Our discussion is organized in the following way. First, we discuss modularity as a framework for developing and deploying strategic capabilities in product market competition. Reflecting the view that 'products design organizations' (Sanchez and Mahoney, 1996), we then explain how modularity in product designs can create embedded co-ordination that enables the modular design of organizations. We go on to explain how modularity in product and organization designs can provide a framework for improving processes for organizational learning and capabilities development. Following this, we suggest how modular product and organization designs facilitate the fusion of intended and emergent strategies in dynamic environments. We conclude by suggesting implications for strategy theory of the feasibility of achieving new forms of strategic flexibility and dynamic capabilities development through modularity in product and organization designs.

Modularity and Strategic Capabilities in Product Market Competition

Complex systems, whether physical or social, exhibit structures and processes that consist, at least to some degree, of 'nearly decomposable subsystems' of components (Simon, 1962). A component in a product design performs a specific function or functions within a system of inter-related components whose collective functioning creates the overall functionality of a product.

A system – whether physical, organizational or technical – may be distinguished as loosely coupled or tightly coupled (Orton and Weick, 1990) by the degree to which its component parts tend to be independent or interdependent in relation to each other. A product design can therefore be distinguished fundamentally by the degree to which the overall product design has been decomposed into 'loosely coupled' versus 'tightly coupled' component designs. The degree to which component designs are tightly or loosely coupled in a product design is determined by the interface specifications, which define the input and output relationships between components and thereby determine how dependent one component's design will be on the designs of other components with which it interacts. Interface specifications define, for example, the way in which components are physically fitted to each other, the way in which power is transferred between components and the way in which communication and control signals are exchanged between components.

Modularity in product designs is created by a special form of standardized component interface specifications. Interface specifications become standardized when they are not allowed to change during a given period of time – for example, during a product development period and perhaps even during the commercial lifetime of a 'generation' of products. Modularity in product designs is created when standardized interfaces are specified in order to permit the introduction of a range of design variations for each type of component in the overall product design. Modular product design therefore creates a loosely coupled system of component designs (Sanchez and Mahoney, 1996), because introducing design variations in one component will not require compensating changes in the designs of other components, so long as all component designs used in a modular product design remain within the range of variations allowed by the standardized interfaces.

Modularity becomes an important source of strategic flexibility in product market competition when a number of different versions of modular components can be readily substituted (Garud and Kumaraswamy, 1993) or 'mixed and matched' (Sanderson and Uzumeri, 1990) in a modular product design to generate a potentially large number of product variations distinguished by different combinations of component-based features, functionalities and/or performance levels (Sanchez, 1991, 1995b). Modular product designs may therefore provide a platform (Wheelwright and Sasser, 1989) for achieving greater product variety at lower design costs, creating the potential for more extensive product differentiation. Modular designs also facilitate both more rapid upgrading and accelerated cost reductions of products by allowing the direct substitution of technologically improved and/or less costly modular components as soon as they become available. These flexibilities derived from modular product designs may improve a firm's capabilities to respond to changing markets and technologies by introducing more product variations more rapidly and at lower cost (Volberda, 1996a).

We suggest that these strategic flexibilities and resultant competitive benefits of modularity, as well as other strategic benefits that we discuss below, are stimulating the increasingly widespread use of modular product designs in markets as diverse as jet aircraft, automobiles, consumer electronics, household appliances, machinery, personal computers, software, test instruments, financial services and power tools (Langlois and Robertson, 1992; Sanchez and Mahoney, 1996; Sanchez and Sudharshan, 1993; Sanderson and Uzumeri, 1990).

Embedded Co-ordination and Modularity in Organization Designs

Traditional engineering design typically follows a methodology of constrained optimization, which results in (production) cost or performance 'optimized' product designs based on functional subsystems of highly integrated, tightly coupled components. In such product designs, the interfaces specified between tightly coupled components must reflect the specific design characteristics of each inter-related component. As a consequence, since even a small change in the design of one component may require extensive compensating changes in designs of many other components, processes for developing products composed of tightly coupled component designs are likely to require intensive communication and co-ordination between component development units. Thus, creating product designs composed of tightly coupled components will require organization designs consisting of tightly coupled development processes in which continuous exercise of managerial attention and authority must be used to co-ordinate highly inter-dependent component development processes. The close and continuous exercise of managerial co-ordination, in turn, usually requires an authority hierarchy that is typically achieved only within the boundaries of a single firm or within a dominant firm and its quasi-integrated component suppliers (see Nishiguchi, 1994). This fundamentally causal relationship between tightly coupled product designs and tightly coupled organization designs is illustrated in Figure 14.1.

Creating modular product designs based on loosely coupled component designs, on the other hand, has far-reaching impacts on feasible organization designs. The standardized interfaces in modular product designs create an information structure (Sanchez and Mahoney, 1996) that defines the required outputs of component development processes. As long as the design created by a component development organization conforms to the standardized input and output interfaces specified for that component by the modular product design, the

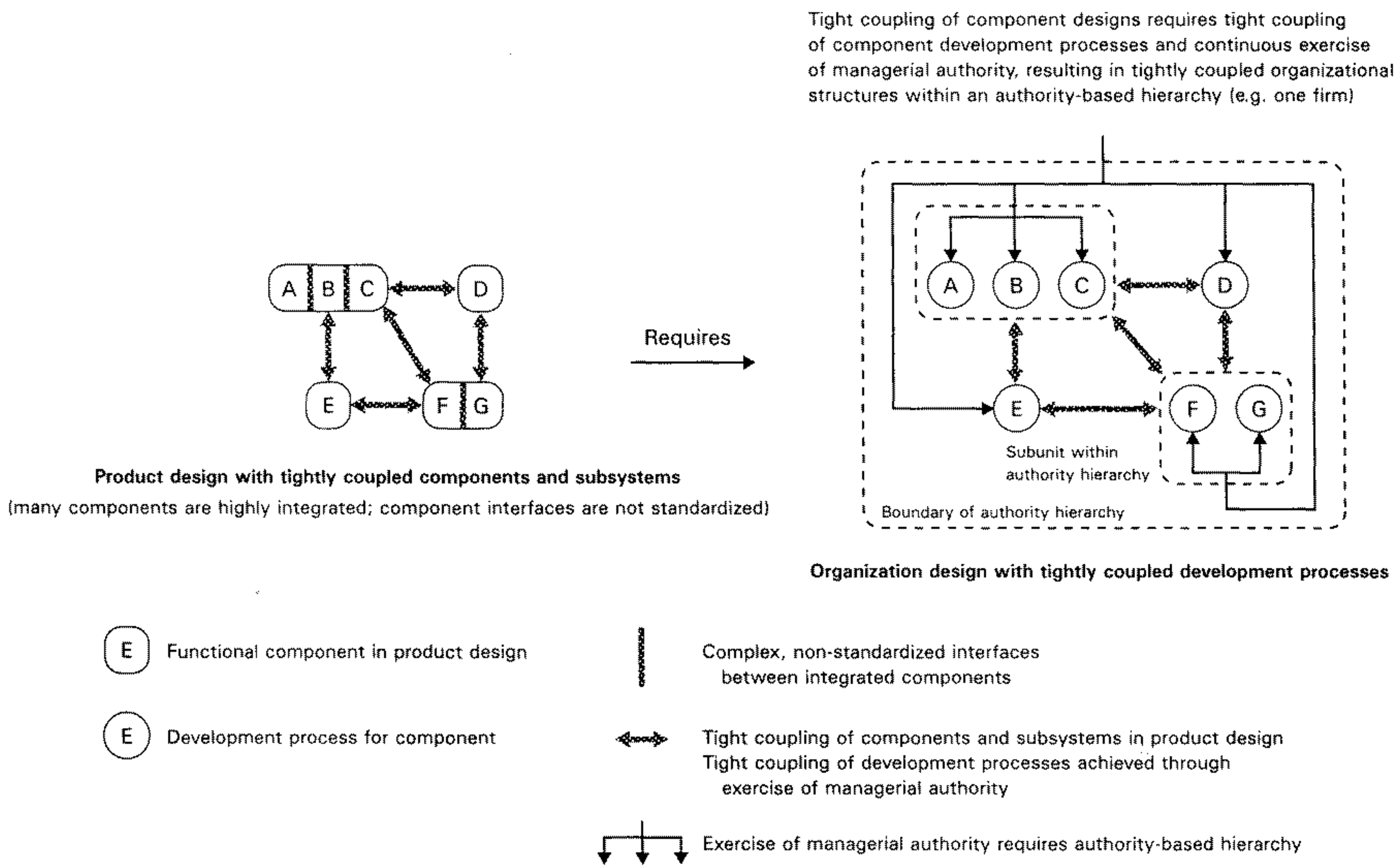

FIGURE 14.1 *Tightly coupled component designs require tightly coupled component development processes*

processes of individual component developers do not need to be managed directly or monitored (except for timeliness) by the firm co-ordinating overall product development. Thus, individual component developers can perform modular component development tasks autonomously, because the essential task of co-ordinating the overall product development process becomes, in effect, embedded in the information structure of required development outputs provided by the standardized interface specifications of the modular product design (Sanchez, 1995a). Moreover, once component interfaces are standardized, thereby establishing the essential features of the required outputs of all component development processes, all component development processes can be carried out concurrently. Thus, modular product design provides a means to achieve hierarchical co-ordination of autonomous and concurrent development processes without the need for continuous exercise of managerial authority, a form of embedded co-ordination that can result from modularity in product designs (Sanchez and Mahoney, 1996).

Firms developing different component variations for modular product designs may therefore be organized into a network of loosely coupled development processes, enabling a loose coupling or modularization of organizational designs for creating and producing products. The enabling relationship between loosely coupled modular product designs and loosely coupled modular organization designs is shown in Figure 14.2.

More generally, we suggest that the degree and nature of the decomposition of a product design fundamentally determines the degree and nature of the decomposition of feasible organization designs for developing that product. Thus, while organizations ostensibly design products, at a more fundamental level it can be argued that products design organization, in the sense that the development (and other) tasks implicit in a given product design largely determine feasible organization designs for developing (and perhaps producing, distributing and servicing) that product (Sanchez and Mahoney, 1996).

Computer-assisted design and development (CADD), computer-integrated manufacturing (CIM) and electronic data interchange (EDI) are recent developments in computer systems that provide standardized information processing interfaces and procedural protocols that further enhance the ability of firms using modular designs to 'quick connect' (Sanchez, 1996b) with other firms using similar information systems. The quick-connectivity between firms made possible by information systems with standardized interfaces can stimulate the formation of 'electronic hierarchies' (Malone et al., 1987) of firms that can be rapidly configured into electronically mediated resource chains to develop, produce, distribute, market and service products (Sanchez, 1995a). As suggested in Figure 14.2, creating standardized interfaces between components in modular product designs, combined with using standardized quick-connect electronic interfaces between firms, may provide the 'interoperability' (Hald and Konsynski, 1993) among firms that enables a global network (Kogut and Kulatilaka, 1994) or 'constellation' (Normann and Ramirez, 1993) of developers and suppliers to create component variations for a wide and changing array of products.

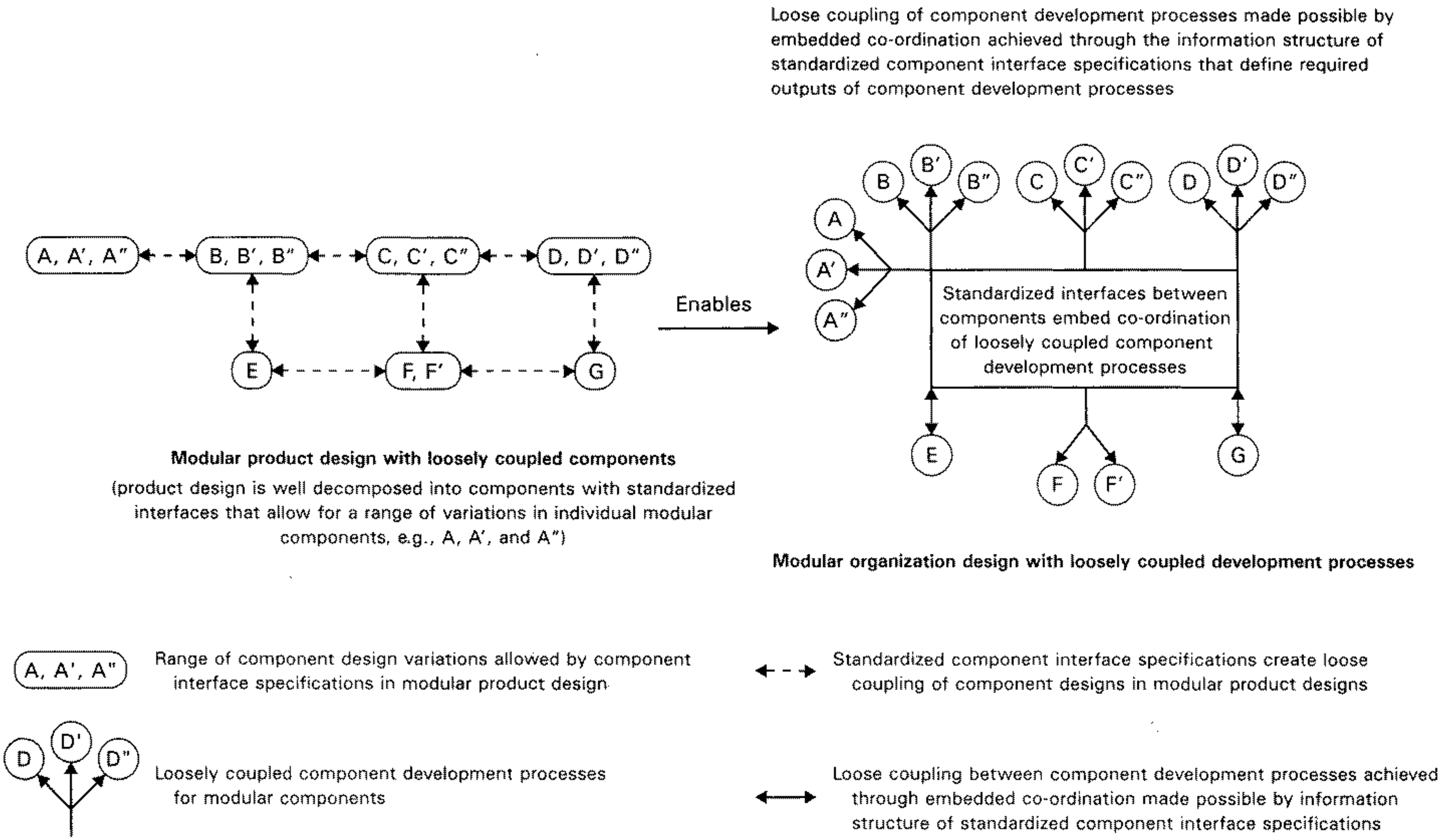

FIGURE 14.2 *Modular product designs enable loosely coupled (modular) development processes*

IKEA's computer-based co-ordination of more than 1800 loosely coupled suppliers of modular ready-to-assemble furniture components is an example of a modular organization for product creation, production and distribution that spans more than 50 countries (Normann and Ramirez, 1993). Boeing's 777 assembly process in Seattle is another example of modularity in product design used to create and co-ordinate a global organization design. Parts of the modular plane's fuselage and passenger doors are made in Japan; parts of the tail and rudder assembly come from Australia; nose cones and flaps are made in Italy; engines come from any of three manufacturers in the USA and England; landing gears come from Canada, France and the USA; some of the electrical systems are made in England; the nose landing gear door comes from Ireland; and parts of the tail, wings and nose sections are produced by the Boeing Company itself in various locations in the USA and Canada. The modular design of the 777, coupled with the standardized interfaces in the information system linking Boeing and its suppliers, makes possible the modular organization of the development, production and delivery processes for this complex aircraft requiring over 3 000 000 parts (Woolsey, 1994).

Modular organization designs made possible by modular product designs and quick-connect interfaces between information systems thus appear to provide a new means to achieve superior speed of competitive response through faster, more diverse and more extensive adaptive co-ordination. The strategic flexibilities to be derived from such quick-response capabilities may substantially increase the ability of an organization to respond to or initiate new product opportunities in dynamic markets (Volberda, 1996b, 1998).

Modularity as a Framework for Organizational Learning and Capabilities Development

The decomposition of a product design into functional components and the information structure represented by the specifications of input and output interfaces between components jointly define a product architecture (Abernathy and Clark, 1985; Clark, 1985; Henderson and Clark, 1990; Sanchez and Mahoney, 1996). We now suggest that modular product architectures may provide a framework both for improving organizational learning processes and for more strategic focusing of capabilities development.

Traditional sequential or 'overlapping problem-solving' approaches to creating new products (Clark and Fujimoto, 1991) typically mix the development of new technologies and new products in a sequential process for developing tightly coupled components. In these approaches, technological uncertainties are resolved progressively through an iterative process of design and redesign of inter-related components until an acceptable product architecture finally emerges from the product development process. In these processes, however, tightly coupled upstream component designs must often be reworked when unanticipated component interactions are discovered during downstream component development processes. Thus, product development by sequential or overlapping component development processes becomes a complex, highly recursive and consequently time-consuming process in which technological learning at both the component level (understanding how components function) and the product architectural level (understanding how components interact) may be stymied by the complex interdependency of architectural and component level learning processes. Tightly coupled processes for joint development of new technologies and new component designs may, therefore, lead to significant inefficiencies in both kinds of learning processes.

Modular product architectures enable a different approach to technological learning in which learning processes at architectural and component levels may be intentionally decoupled and managed as loosely coupled processes (Sanchez and Mahoney, 1996). Fully specifying the standardized component interfaces in a modular product design requires a high level of architectural knowledge about how components will interact in a product design. Thus, modular product architectures must be based on technologies which are well understood at the architectural level before they are used in a product development project. As a result, in creating modular product architectures, technological learning processes at the architectural level must become decoupled from technological learning at the component level. In so doing, however, architectural level technological learning may proceed unimpeded by complex interdependencies with component design processes in specific product development projects. At the same time, within the set of standardized input and output relationships between components established by a current modular product architecture, component level innovation and learning processes can proceed uninterrupted by repeated demands for component design changes that would be likely to occur if processes for developing new technologies and new components were tightly coupled.

The loose coupling of technological learning processes that becomes possible through the use of modular product architectures enables more efficient learning and innovation at the component level to occur within networks of widely dispersed, loosely coupled development organizations. Modularity thus provides a new framework for loose coupling of architectural and component level learning that may reduce path-dependency effects by increasing the resources and organizational forms available to firms in developing new technological capabilities at both architectural and component levels.

Modular product architectures also provide a framework for integrating technological learning at both architectural and component levels with market learning about both long-term trends and current opportunities (Sanchez, 1995b), as shown in Figure 14.3. Long-term planning for product architectures that may serve as platforms for future generations of products provides a structured framework for conceptualizing and evaluating possible future product strategies. Defining the essential characteristics and desired flexibilities of future product architectures provides a process for integrating perceived long-term technological and market trends, as well as identifying possibilities for the firm's own initiatives to influence both trends. Periodic creation of new product architectures provides a structured framework for applying a firm's own or otherwise addressable technological and marketing capabilities to medium-term market opportunities. The flexibility to leverage product variations by mixing and matching

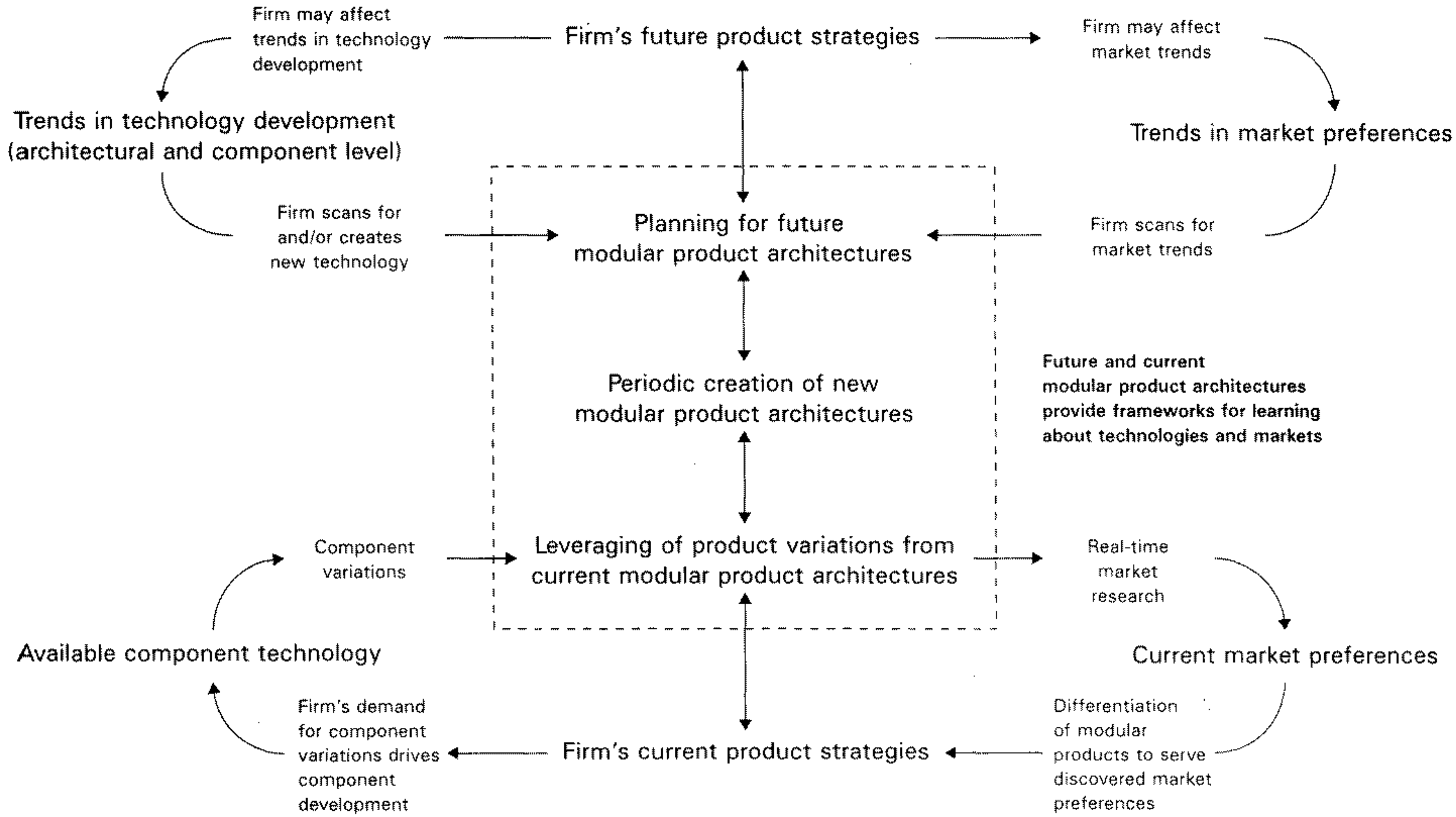

FIGURE 14.3 *Modular product architectures as structured and flexible frameworks for technology and market learning*

component variations within a current modular product architecture provides a framework for intensified short-term technological and market learning. The flexibility to mix and match component variations facilitates market learning by enabling extensive differentiation of products to discover market preferences – a process Sanchez and Sudharshan (1993) have termed 'real-time market research'. At the same time, developing new component variations to serve the demand for product variations that can be leveraged from a current modular product architecture provides a framework for focused technological learning and innovation at the component level. Thus, modular product architectures can provide both a more structured and a more flexible framework for building and linking the firm's technological capabilities at several levels with improved capabilities for learning about and responding to market trends and current opportunities.

It might seem that using modular product architectures intentionally to decouple organizational learning processes, especially those carried out through global networks of firms, might obstruct sharing of learning between organizations and, consequently, limit the combinative capabilities that may be derived from cumulative knowledge (Bartlett, 1993; Kogut and Bowman, 1994; Kogut and Zander, 1992). When modular product architectures are effectively combined with quick-connect information systems, however, modularity appears to facilitate an evolutionary process of technology development and market testing that supports accelerated knowledge building and capabilities development within networks of firms (Baldwin and Clark, 1994; Sanchez, 1996a). CADD's standardized interfaces and protocols for co-ordinating design, communications, scheduling and documentation, for example, ensure that all participants in a product creation process can, in effect, analyse problems and document decisions in ways that are visible to all participants. Accessible archives of design decisions and feedback on product performance provide an audit trail of the lessons learned in development projects, which can contribute to a growing organizational memory (Walsh and Ungson, 1991) within the network of linked firms. Modular product architectures and quick-connect information systems may, therefore, join to create platforms for sharing structured and detailed knowledge throughout networks of participating organizations.

Modularity as a means to Achieve the Fusion of Intended and Emergent Strategies

Effective and efficient organization design is a central concern of organization theory and strategic management (Williamson, 1993a). This concern was anticipated by the early debate in economics between proponents of economic organization by planning (Lange, 1936), who argued that co-ordination by planning was both possible and workable, and proponents of markets (Hayek, 1945) who argued that markets have superior efficiency in handling rich and dispersed information and, therefore, in co-ordinating intricately inter-related economic activities. Hayek (1978: 183), for example, emphasized the notion of 'human action without human design', resulting in an emerging 'spontaneous order'.

The Lange–Hayek debate over planning versus spontaneous ordering in economies at large has counterparts in the field of strategic management, including the Ansoff–Mintzberg debate over the merits of strategic planning versus emergent strategies at the firm level (Ansoff, 1988, 1991; Mintzberg, 1990a, 1991). Mintzberg's (1978) emergent strategies, for example, are reminiscent of Hayek's (1978) 'spontaneous ordering' in asserting that specific, coherent patterns of action cannot be delineated adequately by any one mind ex ante, but may only emerge and be apprehended by many participants ex post.

Williamson (1991) adds a further perspective by suggesting that the 'institutions of capitalism' allow for adaptation within an institutional framework and can thus be seen as supporting both planned and spontaneous ordering. In a similar vein, we suggest here that modular product and organization designs offer strategic management a new framework for the conceptual synthesis of planning and emergence. More specifically, the creation of modular product architectures and the use of quick-connect information systems to enact modular organizations appear to be powerful new means for achieving an intended (planned) strategy of providing a range of flexible (emergent) responses to an uncertain environment. In essence, emergent configurations and deployments of specific product and organization variations derived from the flexibilities of planned modular product and organization designs enable the playing out of a range of emergent strategies in response to environmental change. Strategic flexibility achieved through creating modular product and organization designs may, therefore, be an overarching strategy that allows the coherent conceptual fusion of intended and emergent strategies.

Williamson, elaborating on Simon's (1962) notion of hierarchies in complex systems, also proposed a hierarchical decomposition principle for organizational structure, stipulating that:

> ... internal organization should be designed in such a way as to effect *quasi-independence* between the parts, the high-frequency dynamics (*operating activities*) and low-frequency dynamics (*strategic planning*) should be clearly distinguished, and incentives should be aligned within and between components ... (1986: 146; our emphasis)

In this regard, we suggest here that under dynamic conditions in product markets, the most viable organizational form may be a strategically flexible firm capable of exercising a range of emergent product market initiatives (high-frequency dynamics) made possible by the planned creation of modular product architectures (low-frequency dynamics). Moreover, the embedded co-ordination that can be achieved through the standardized interfaces of modular product designs may enable extension of the hierarchical decomposition principle beyond the boundaries of one organization to include a potentially large number of loosely coupled organizations. In essence, the embedded co-ordination of modular product architectures may provide a fundamental means of achieving flexible hierarchical organization both within individual organizations and through networks of loosely coupled modular organizations.

Implications for Strategy Theory

A useful tool for strategic management and organization science is to make use of the world's failure to describe the complexity of our world as simply as possible (Simon, 1981: 222). Better understanding of the potential decomposability of complex organizational phenomena into loosely coupled subsystems may be a key to gaining new insights into the fluid structures and new organizational dynamics of many contemporary product markets.

Simon further notes that, '... design is concerned with the discovery and elaboration of alternatives' (1982: 419). Modularity in product and organization designs may provide strategic managers in dynamic markets with a new means to create strategic flexibilities that make possible a broader range of strategic alternatives. Growing use of modular product designs may also explain at least in part the accelerating de-integration of both product creation and production processes and the resulting rise of both networks of organizations and increasingly dynamic markets in the 2000s.

Apprehending the dominant logic for successfully competing in current markets is a primary goal of strategic management (Prahalad and Bettis, 1986). While commitment has often been invoked in strategy theory as a key concept for ex post explanations of economic rents (for example, Ghemawat, 1991), strategic flexibility now appears to be a key concept for understanding successful ex ante strategizing under uncertainty (Sanchez, 1993, 1995a). In effect, strategic flexibility may be thought of as the condition of having options for managing the evolving uncertainties of the present and future, while commitment can be seen as the condition of having exercised one or more strategic options in the past. Further, while it is common in the resource-based view within strategy to argue that a firm's commitments provide isolating mechanisms that deter entry by would-be competitors (Mahoney and Pandian, 1992; Rumelt, 1984), it is now becoming apparent that superior product design flexibility and manufacturing flexibility may also deter entry, especially in dynamic product markets (Chang, 1993). Thus, we suggest that strategic flexibility achieved through modular product and organization designs may be a new dominant logic for successful product-based competition in dynamic markets (Sanchez, 1995a).

Strategic flexibility achieved through modularity in products and organizations may also permit a synthesis of intended strategy (wherein modular product and organization designs are intendedly created as flexible vehicles for accommodating change) and emergent strategy (wherein firms leverage modular product variations and reconfigure resource chains as technologies evolve and new market preferences are discovered). The recent growth of real-time market research by Sony and other firms, for example, suggests how the flexibility of modular product designs can be used to achieve rapid product adaptation as evolving preferences are discovered in new product markets (Sanchez and Sudharshan, 1993; Sanderson and Uzumeri, 1990). Moreover, strategic flexibility can enable more than just a dynamically efficient adaptive response to the uncertainty of turbulent markets. Superior flexibility achieved through modular designs can also be used proactively to create turbulence and uncertainty in product markets that less flexible competitors may not be able to respond to readily (Gerwin, 1993).

In investigating the strategic impact of modularity in product and organization designs, we are heeding Williamson's (1976: 102) advice to investigate 'transactional phenomena [at] ... the semi-microanalytic level of detail'. This perspective has led us to suggest some extensions to concepts of dynamic capabilities in current strategy theory, including:

1 extending the resource-based view's emphasis on commitment to specific-use resources and capabilities to include recognition of the strategic value of flexible resources and capabilities in dynamic markets, e.g. modular product and organization designs
2 explaining new forms of competitive product strategies in which use of modularity to achieve embedded co-ordination of modular organizations may create new levels of strategic flexibility
3 suggesting ways in which modularity provides a framework for more effective learning and development of organizational capabilities
4 proposing that the perceived dichotomy of intended and emergent strategies in strategy theory can be resolved through a concept of strategic flexibility (obtained through modular product and organization designs) that enables a fusion of planning and emergence.

from

Rethinking Strategy

edited by

Henk W. Volberda and Tom Elfring

SAGE Publications
London • Thousand Oaks • New Delhi
2001