Modular architectures, knowledge assets and organizational learning: new management processes for product creation

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Abstract: This paper considers the impacts of adopting *modular product and process architectures* on the organization of product creation processes and on the kinds of organizational learning which can take place within modular product creation processes. The discussion elaborates the concepts of modular product and process architectures and explains how use of modular product and process architectures influences an organization's knowledge, in effect creating *modular knowledge architectures* in an organization. Effective management of modular knowledge architectures enables greater clarity in identifying an organization's current knowledge assets and greater precision in targeting strategically useful organizational learning. Adopting modular architectures leads to changes not only in the nature of the technological work performed in an organization, but also in the kinds of knowledge assets the organization creates, the way learning occurs at both individual and organizational levels, and the human resource characteristics of the organization. These changes in turn call for complementary changes in performance assessment metrics, incentive structure designs, the nature of the employment relationship, and the management practices of an organization, especially with regard to the management of creative processes.

Keywords: knowledge architecture; knowledge management; modularity; organizational learning; process architectures; product architectures; product creation; self-managing processes.

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1 Introduction

Managing the architectures of an organization's products and processes is increasingly being recognized and developed as a critical strategic management activity [1–6]. In the pursuit of overtly architectural approaches to managing products and processes, new interrelationships and interactions between the architectures of an organization's product designs and its organization designs are being recognized and elaborated [7,8]. In particular, the increasing use of modular product and process architectures by technology-intensive firms in many industries makes understanding modular product creation processes a key requirement for more effective strategic management of technology-intensive organizations. This paper considers the impacts which the adoption of *modular product and process architectures* can have on the organization of product creation processes, on the kinds of organizational learning that take place during product creation activities, on the interactions of individuals and work groups, and on the requirements for effective management of product creation as a strategic value-creating activity.

This paper adopts an institutionalist approach [9,10] and draws on the institutional perspective of adaptive structuration theory [11,12] to characterize the change processes an organization may undergo when it adopts modular product and process architectures as the framework for coordinating its product creation processes. This theoretical approach seeks to identify both the structure and the spirit of a technologically motivated change process [13] such as the adoption of a modular framework for product creation.

The structural aspects of a technological change process concern changes in the 'rules and resources' that drive alternative technical systems. Foremost among the structural changes which accompany adoption of modular architectures are new 'design rules' to be followed in product definition, design, and development processes. Following modular design rules in product creation processes enables and often leads to new subdivisions of work within development activities, to new kinds of team-based and network-based work processes within an organization, to new work roles for individuals within teams and networks, and to new individual and organizational learning processes. Such changes in work processes lead to the creation of new kinds of resources within a technical system, including new kinds of information, new forms of knowledge, new capabilities to apply knowledge to new purposes, and often new kinds of physical infrastructure.

Following the new rules of a new technical system not only leads to changes in technological work activities and related human capabilities, but also precipitates new patterns of social interactions that embed the new technical system in a specific organizational context, creating what is essentially a new sociotechnical system with a distinct new culture or spirit [13]. The spirit of a sociotechnical system has to do with the 'values and goals' that motivate the social interactions within a sociotechnical system. When a sociotechnical system undergoes change, each new technical process within the organization will evolve values and goals that shape the way people individually and collectively interact within a given technical and social context (see, for example, van de Kraats and Thurlings [14]). The values and goals that an organization eventually adopts during a period of sociotechnical change can have profound impacts on the objectives an organization pursues through the new technical system and on how well it performs in pursuing those objectives.

Building and leveraging new organizational competencies [15] based on the use of modular architectures therefore requires more than just adopting new design rules and creating the new resources required by a new technical system. Managers must also guide the emergence of new values and norms in the cultural change process that will accompany an organization's conversion to modular product creation processes. Managers must attend to key human resources aspects of an organizational shift to modular architectures, including defining new ways of assessing individual and team performance, designing new kinds of incentive systems, and developing new management processes for encouraging and guiding an organization's processes for product creation.

In the following discussion, Sections 2 to 4 discuss the interrelationships of product, process, and knowledge architectures. Sections 4 to 6 assess the organizational learning and other organizational and human impacts of adopting modular product and process architectures in product creation and realization.

Section 2 defines product architectures. It distinguishes modular product architectures based on design rules for creating product designs as systems of 'loosely-coupled' component designs from traditional product architectures based on design rules that typically lead to product designs with 'tightly-coupled' component designs. Following modular design rules that create the loose coupling of component designs within a product architecture results in a *flexible product architecture* that can be used to leverage product variations by substituting [16] and 'mixing and matching' [6] modular component variations. Flexible modular architectures make possible new kinds of product strategies that invite significant changes in the way product creation is organized and managed.

Section 3 defines process architectures. Drawing on the principle that 'products design organizations' [7], Section 3 explains how the design rules an organization adopts for creating product architectures fundamentally constrain the feasible organization designs an organization can adopt for creating, producing, and supporting its products. The section explains how creating loosely-coupled component designs within a modular product architecture makes possible the loose-coupling of activities for creating, producing, and supporting products, thereby allowing many of an organization's product creation and realization activities to be carried out concurrently and autonomously by self-managing teams working within the *information structure* of a modular product architecture.

Section 4 explains how the knowledge an organization develops in product creation and realization becomes structured around its product and process architectures. The section explains how adopting modular product and process architectures helps an organization to identify the component and architectural forms of knowledge that make up an organization's knowledge architecture. Use of modular product and process architectures improves an organization's ability to identify specific opportunities to develop strategically valuable new knowledge assets that can improve its capabilities in product creation and realization. Further, by decomposing product and process architectures into systems of loosely-coupled components and activities, modular product and process architectures create *loosely-coupled knowledge domains* in which reduced complexity facilitates greater efficiency in learning about technologies and markets. Section 4 also explains how architecturally coordinated teams 'learn-by-leveraging' product variations from current product and process architectures in the near term and 'learn-by-planning' for future generations of architectures in the mid and long terms. The section explains how modular architectures provide information structures that enable learning processes to be carried out through architecturally coordinated self-managing team processes.

Section 5 identifies some new kinds of technological work to be performed in creating and managing modular product and process architectures. This discussion distinguishes the technological work of product and process 'architects' from that of 'component specialists' in modular product creation processes, and it examines the roles which each type of knowledge worker plays in supporting the organizational dynamics of *synthesis and decomposition* that characterize modular product creation processes.

Section 6 considers the need for defining new performance measures, new incentive designs, and new employment relationships for knowledge workers in modular product creation processes.

A concluding section offers observations on the new management processes – one might even say, the *new management style* – required to guide the creation and use of modular product and process architectures, particularly with respect to the management of individual and team creative processes.

2 Product architectures

Products – whether services, software, or assembled goods – are composed of discrete functions that work together to provide users with the overall attributes and functionalities that distinguish a given product in the marketplace. A product creation process develops a new product design by decomposing the 'bundle of product attributes' [17] desired in a new product into a system of discrete functional components that interact to provide the overall functionality of the product [18].

A *product architecture* is created when 1) a new product design has been decomposed into a system of functional components [19] and 2) the ways in which individual components interact with other components have been fully specified [4,7,20]. The component interface specifications in a product architecture define essential component interactions, such as [21]:

- how one component is physically connected to another ('attachment interface');
- how power or material is transferred between components ('transfer interface');
- how the state of one component will be communicated to and/or controlled by other components ('control and communication interfaces');
- the spatial location and volume a component may occupy ('spatial interfaces');
- various ways in which the functioning of one component may generate heat, magnetic fields, vibrations, or other environmental effects that must be accommodated by other components ('environmental interfaces').

As a system of interrelated functional components, a product architecture may be distinguished by the extent to which its component designs are tightly coupled or loosely coupled [22] – i.e. by the degree to which the component designs that make up the system tend to be interdependent or independent in their interactions with each other. The degree to which component designs are tightly or loosely coupled in a product architecture is fundamentally determined by the interface specifications which define the input and output relationships between components. A modular product architecture is a system of loosely-coupled component designs [7] that is created by standardizing component interface specifications – i.e. not allowing interface specifications to change during some period of time – and by specifying component interfaces to allow for substitutability [16] of variations in component designs within the product architecture.

By enabling the substitution or 'mixing and matching' of component variations [23], modular product architectures make it possible to leverage a potentially large number of product variations distinguished by different combinations of component-based features, functionalities, and/or performance levels [4,24,25]. Thus, modular product architectures become a means to achieve several forms of *strategic flexibility* [3,5,18]:

- *Ability to create greater product variety* by leveraging product variations based on new combinations of component variations with different performance characteristics. This flexibility of modular product architectures is now being used to offer expanded ranges of product variations in industries as diverse as automobiles, consumer electronics, home appliances, object-oriented software, banking services and power tools [7,21,26].
- *Ability to develop and introduce technologically upgraded products more quickly* by creating modular product architectures that can accommodate both currently available components and technologically improved components expected to become available within the intended lifetime of the product architecture. The ability to substitute technologically improved components directly into a modular product architecture enables more rapid introduction of upgraded product models as soon as improved components become available. This flexibility of modular product architectures enabled Sony to introduce four upgraded models of its HandyCam product within a 22-month period [27].
- *Greater speed to market.* Because the inputs and outputs of each component are fully specified and standardized in a modular product architecture, modular component designs may be developed in concurrent component development processes [7], allowing substantial reductions in product development cycles and enabling greater speed to market.
- *Lower design, production, distribution, and service costs.* Leveraging product variations from a single modular product architecture may substantially reduce design costs per product variation introduced. Economies of scale can also be realized when 'common components' or 'standard designs' can be used across product variations. When the component variations that differentiate an individual product model can be added at a 'late point' in the production or distribution process, the reduced variety of parts used in assembly or held in inventory reduce production and distribution costs per product variation introduced. Hewlett-Packard serves various regional and national markets for its ink-jet printers, for example, by producing a universal printer architecture to which a modular power supply component can be added in regional distribution centres to suit local electrical requirements [28]. Modular product architectures may also significantly change product service requirements by enabling the 'design-in' of self-diagnostic capabilities and of easily replaced modular components that radically lower field service costs [8].

3 Process architectures

Analogous to a product architecture, a process architecture is a decomposition of a process into its component functional activities and a specification of the interactions (interfaces) between those activities. Like the components of a product architecture, the activities that compose a process architecture may be either tightly or loosely coupled.

Creating modular product architectures based on loosely–coupled component designs can have profound impacts on feasible organization designs for developing new products. Figure 1 contrasts the conventional and modular approaches to creating product architectures. Fully specifying and standardizing component interfaces in modular product architectures *at the beginning* of a product creation process creates an *information structure* that defines the required outputs of component development processes [7]. As long as the component designs created by component development groups conform to the fully defined and standardized input and output interface specifications of a modular product architecture, the activities of individual component development groups can be carried out concurrently. In addition, component development tasks can be performed by component development groups that are largely self-managing, because the coordination of the overall product development process is 'embedded' in the information structure of required development outputs provided by the standardized interface specifications of the modular product architecture [3]. Component development processes can become, in effect, loosely-coupled, self-managing processes coordinated by the information structure of a modular product architecture [29].

Figure 1 Comparison of product definition, design and development in conventional versus modular product creation

	definition	*design*	*development*
conventional product creation	Attributes of 'optimal' product are determined by market research.	Desired functionality is decomposed into functional components, but component interfaces evolve during component development.	Component designs and interfaces co-evolve in a recursive process. Product architecture is determined by interfaces between final component designs and is thus an output of the development process.
modular product creation	Product architecture is conceived as a vehicle for leveraging product variations and upgraded models.	Before beginning of component development, standardization of fully specified component interfaces defines input and output requirements for component designs to be developed.	A fully defined product architecture (in the form of standardized component interface specifications) is the primary input to and driver of component development processes. The information structure of the fully defined product architecture allows component development processes to become concurrent and self-managing.

Extending this view of the interactions of organization designs and product designs, it can be argued more generally that *products design organizations*, in the sense that the development, production, distribution, and service tasks implicit in an organization's product designs largely determine the feasible process architectures an organization can adopt for developing, producing, distributing and servicing its products leveraged from the product architecture [7]. Thus, the loose coupling of component designs in a modular product architecture can make possible the loose coupling or 'modularization' of the processes of developing, producing, distributing and servicing products composed of combinations of modular components [8].

Computer–assisted design (CAD), computer–integrated manufacturing (CIM) and electronic data interchange (EDI) provide standardized information processing interfaces and procedural protocols that enable loosely-coupled processes for creating and realizing modular products to 'quick connect' [18] in forming a network of modular product creation and realization processes. Thus, standardizing interface specifications between components and standardizing electronic interfaces between firms are essential steps in creating 'interoperability' [30] among networks of firms engaged in creating and producing components, as well as assembling, distributing, and servicing products [31]

4 Knowledge architectures

We next consider ways in which the use of modular product and process architectures impacts an organization's knowledge structures, the kinds of knowledge an organization develops and the processes through which it learns. In each case, we consider several ways in which the use of modular product and process architectures impacts the learning processes of development teams.

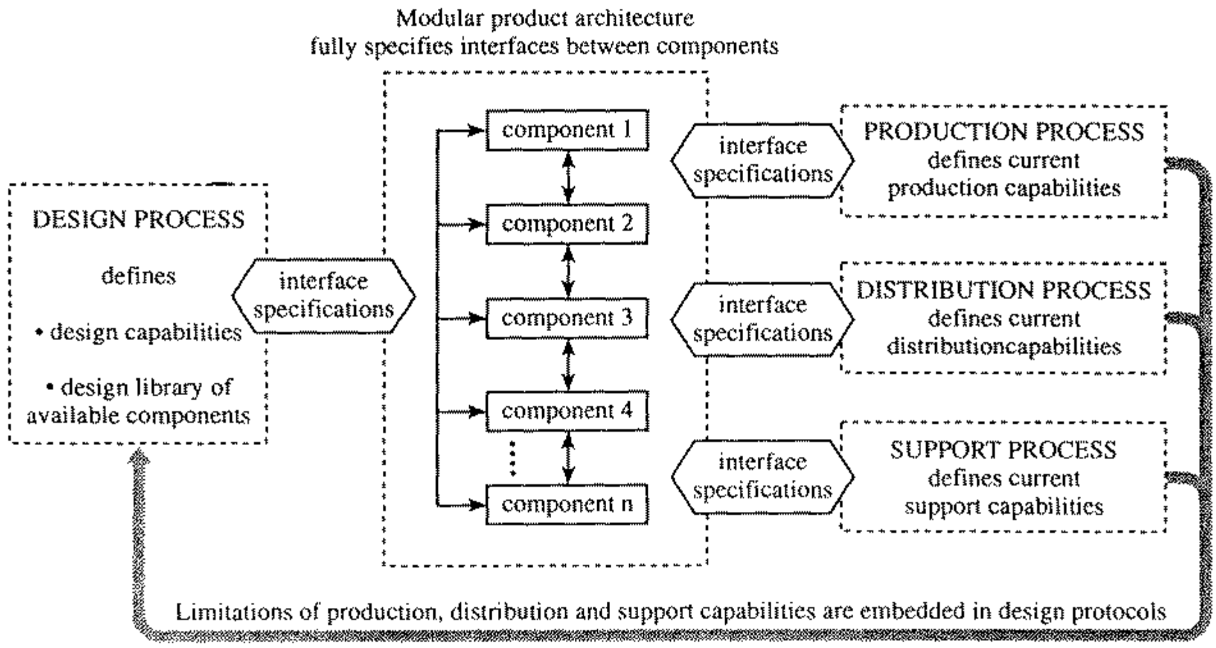
4.1 Impacts of architectures on organizational knowledge structures

Both conventional and 'overlapping problem-solving' [32] approaches to creating new products typically try to develop new technologies and new products at the same time. In these approaches, technological uncertainties are resolved through an iterative process of design and redesign of interrelated components until an acceptable product architecture – i.e. a set of component interface specifications – finally emerges from the product development process. In these processes, learning about technologies (e.g. how a technology can be made to work in a new kind of component), architectures (understanding how various kinds of components interact), and components (understanding how specific components function) may be made difficult by 1) uncertain and complex interdependencies among new technologies, new architectures, and new components, and 2) the changing nature of those interdependencies when component interfaces are allowed to evolve during product development.

Modular product architectures both enable and require a different approach to technological learning in which learning processes for new technologies, new architectures, and new components are intentionally decoupled and can thus be managed as loosely-coupled processes [7]. Because fully specifying the component interfaces in a modular product architecture at the beginning of a development project requires a high level of architectural knowledge about how components will interact in a product design, modular product architectures must be based on technologies and components that are well understood at the architectural level before a product development project using those technologies and components is undertaken. Thus, the development of new technologies must be decoupled from and precede the development of new modular product architectures. Similarly, development of new component variations must take place within the standardized input and output relationships between components established by a modular product architecture, allowing learning processes at the component level to become decoupled from processes for creating new technologies or architectures. The intentional decoupling of technological, architectural and component development in this way creates *loosely-coupled knowledge domains* in which reduced uncertainty and complexity can lead to more efficient learning processes in all three domains [7,33].

Figure 2 suggests how modular product and process architectures create modular knowledge architectures [5] composed of loosely-coupled knowledge domains. At the centre of Figure 2 is a modular product architecture represented by a system of loosely-coupled components whose interactions (represented by the arrows linking components) are fully defined by standardized component interface specifications. The standardized specifications of component interactions may be articulated, for example, in the form of 'interface documents' [34] and/or of design protocols in CAD systems that constrain the ways in which components may be interrelated by product designers [18]. Such interface specifications and design protocols, when they exist in an organization, comprise the core of the *design rules* the organization follows in creating new products. In some organizations, interface specifications and design protocols may also be supported by archival documents that detail an organization's knowledge about how components of different types behave and interact in a product architecture.

Figure 2 Modular product and process architectures provide framework for defining knowledge architectures



Fully defining component interface specifications and design protocols forces a firm to document the state of its technical understanding about the components it uses and their interactions – in effect creating a 'balance sheet' of the firm's architectural and component knowledge that is useful in creating new products. Moreover, trying to fully specify the component interfaces in a modular product architecture is very likely to reveal any knowledge deficiencies or 'capability bottlenecks' that limit an organization's understanding of how the components in its product architectures behave and interact. Thus, creating modular architectures becomes a vehicle not only for clearly defining what a firm currently knows about components and their interactions, but also for identifying specific forms of new knowledge which would improve the ability of the firm to create new products.

In a similar manner, the activities that make up an organization's current process architecture for producing, distributing and supporting its products can be defined and incorporated into design rules that guide designers in creating new products that the organization is currently capable of producing, distributing and supporting. These design rules take the form of interface specifications stating how each major component in a product architecture interacts with the major activities in a firm's process architecture, as indicated by the large 'interface specification' arrows in Figure 2. Once an organization's current process capabilities and their feasible interactions with its product architectures are articulated and documented [35], learning within an organization's various process activities can become loosely-coupled. Trial-and-error learning and experimentation within one process activities need not affect or be affected by learning initiatives in other process activities or within a product architecture, so long as changes undertaken in one process do not change the way that process interacts with other processes or with current product architectures. Thus, clearly defining process activities and standardizing their interfaces with other process activities and with current product architectures creates loosely-coupled process knowledge domains that reduce the complexity of those activities and thereby facilitate organizational learning.

4.2 *Impacts of architectures on knowledge assets*

Management researchers have begun to recognize the need for new concepts for identifying and classifying different kinds of organizational knowledge [5,29,36,37]. We next consider how modular knowledge architectures help to identify and codify know-how, know-why, and know-what [5,29] forms of organizational knowledge.

Figure 3 provides summary descriptions of know-how, know-why and know-what forms of organizational knowledge. A firm's know-how is its 'practical understanding' about the current state of a system [38], such as an organization's understanding of how its current products and processes function as systems. Know-how knowledge enables a firm to continue 'operating' its current systems, like leveraging product variations from its current product architecture or maintaining production activities within its current process architecture.

Know-why is the 'theoretical understanding' of the principles governing the functioning of a system [38]. Know-why enables an organization to make significant changes to an existing system or to design a new system. Within product architectures as systems, know-why knowledge is the theoretical understanding of why specific components in a product architecture behave and interact as they do. Similarly, within a process architecture as a system, know-why is the understanding of the principles that govern how processes may be configured to work together. Know-why knowledge enables a firm to make significant changes in existing product or process architectures or to develop new product or process architectures.

Figure 3 Know-how, know-why and know-what forms of knowledge

form of knowledge	*level of understanding*	*capability derived from knowledge*
know-how	'practical understanding' of how a current system works	enables firm to maintain operations using current product and process architectures
know-why	'theoretical understanding' of why a system works	enables making significant changes in current architectures and/or creation of new architectures
know-what	'strategic understanding' of purposes to which know-why and know-how may be applied	enables firm to define feasible new product concepts based on kinds of product and process architectures

Know-what is the 'strategic understanding' of the purposes to which specific forms of know-why and know-how knowledge may be applied in creating product and process architectures [5,29]. Know-what knowledge is the understanding that enables managers to imagine and define feasible new kinds of products and processes for developing, producing, and marketing new products. Know-what knowledge is, in effect, the form of understanding that enables managers to make conjectures about possible new kinds of products and processes.

Figure 4 Forms of organizational learning in modular architectural product creation processes

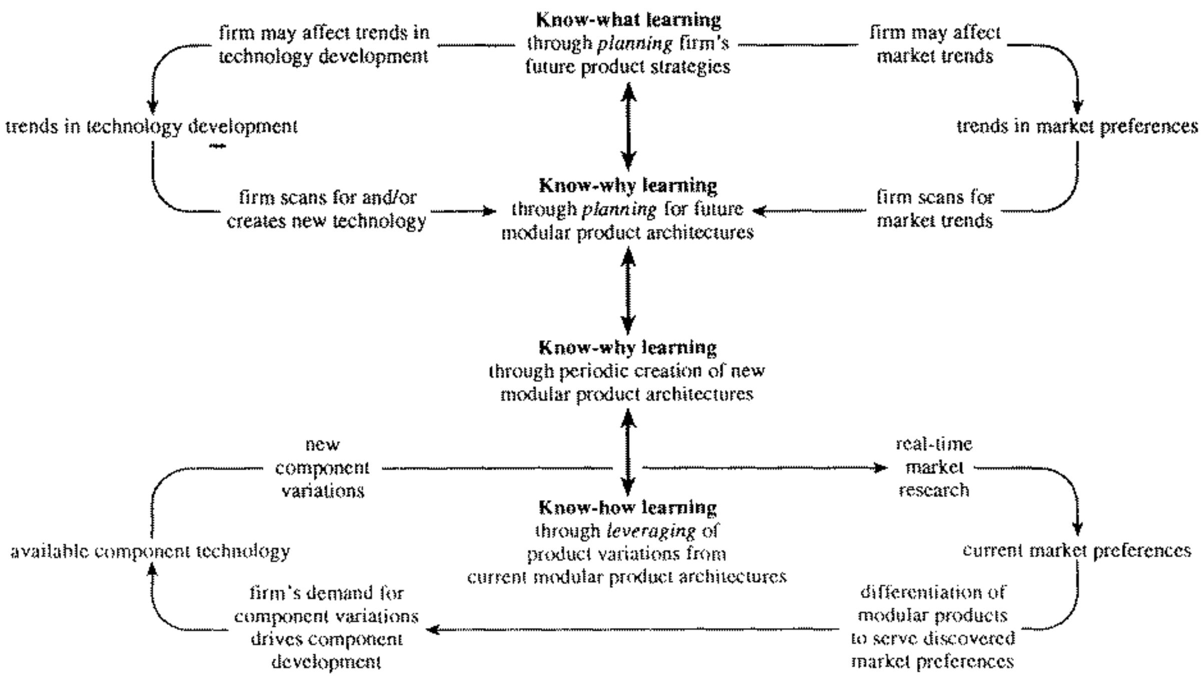


Figure 4 suggests how the use of modular product and process architectures facilitates know-how, know-why, and know-what forms of organizational learning. Know-how learning in developing, producing, and assembling new variations of current types of products is improved by being carried out within the reduced complexity of well defined product and process architectures [7]. The efficiency of know-why learning can be increased by being focused on technologies and components that may be used in the next generation of modular product and process architectures. Know-what learning can be focused on defining future product concepts and related product and process architectures that can respond to future technology and market trends most advantageously. Although many organizations try to forecast technology and market trends, relatively few use those forecasts as inputs for conjecturing future product and process architectures. Conjecturing future product and process architectures, however, can be a very effective way to give content and focus to the 'corporate imagination' [39] and to define specific targets for 'stretch and leverage' of organizational capabilities [40] in creating and realizing new products.

4.3 Architectures as frameworks for 'learning-by-leveraging' and 'learning-by-planning'

Modular product architectures also provide a framework for technological *learning-by-leveraging* in the near term and *learning-by-planning* for longer term product and process architectures, as suggested in Figure 4.

The flexibility to leverage product variations by 'mixing and matching' component variations within a current modular product architecture provides a framework for intensified learning-by-leveraging through extensive market testing with modular product variations – a process Sanchez and Sudharshan [27] have termed 'real-time market research.' Long-term planning for future product architectures provides a structured framework for learning-by-planning by institutionalizing processes for conceptualizing the future product and process architectures required to support future product concepts and strategies. Defining the essential functionalities and desired strategic flexibilities of future product and process architectures provides a process for learning through integrating expected long-term technological trends (e.g. 'technology roadmaps') and market trends, as well as identifying possibilities for a firm's own initiatives to influence both trends. In the mid term, periodic definitions of next-generation product and process architectures provide a structured planning framework for applying a firm's current capabilities and its 'firm-addressable' resources [15] to creating next-generation modular architectures.

Both learning-by-planning and learning-by-leveraging can be carried out by architecturally coordinated self-managing team processes [29]. The interface specifications of current and planned modular product and process architectures provide an information structure that can direct and coordinate concurrent learning processes by development groups in support of current and future product strategies.

5 New kinds of technological work and specializations

Williamson [41,p.46], elaborating on Simon's [42] notion of hierarchies in complex systems, proposed a hierarchical decomposition principle for organizational structure, suggesting 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...." [italics added for emphasis]

Modular product and process architectures are powerful new means for integrating (relatively) low-frequency strategic planning processes for modular architectures that are capable of supporting high-frequency, flexible, emergent responses to changing market opportunities. Modular product and process architectures therefore provide a critical new framework for the planned development of the organizational capacity for spontaneous action.

The complementary strategic processes of planning for modular architectures and of emergent use of the flexibilities of modular architectures are realized through several alternating processes of synthesis and decomposition occurring during the planning, creation, and use of modular product and process architectures. Figure 5 details key cycles of synthesis and decomposition in the evolution of a modular product architecture from its conception in long-term planning for a future generation architecture to the eventual leveraging of a current-generation architecture, as suggested in Figure 4.

The technology development processes of *synthesis* in Figure 5 are carried out by new kinds of technology workers, often called 'architects', whose task is to define the decompositions of a new product into functional components and to fully define component interface specifications. The tasks in the *decomposition* stages of the process are carried out by technology workers who are specialized in developing specific kinds of components.

The cycles of synthesis and decomposition in creating a modular product architecture begin with a synthesis of technology and market forecasts whose objective is the identification of the new kinds of functionalities to be developed and delivered to the market in future product concepts. This synthesis is followed by a decomposition of the desired functionalities into new (or perhaps existing) functional components that can provide the functionalities desired in future product concepts. This decomposition process provides a statement of functional requirements at the component level that enables component development specialists to begin to define and explore the technological implementation of new or improved functional components for future product concepts.

As new types of components or improved components are developed and their basic 'generic' input and output requirements are defined, a second cycle of synthesis is carried out by architects who synthesize the basic descriptions of new and reusable functional components into a definition of specific future product and process architectures capable of supporting the targeted future product concepts. In this stage in the evolution of a modular product architecture, architects carry out system integration at the *design stage* that leads to organizational learning about how new kinds of components may interact with other components in a product architecture.

Once a future modular product architecture is defined (i.e. once component interfaces are specified in the system integration stage), the next step in creating a new product architecture is a decomposition into concurrent component development activities carried out by component specialists. During the development and proving of component designs, organizational learning at the component level may take place as alternate component design concepts are explored and evaluated.

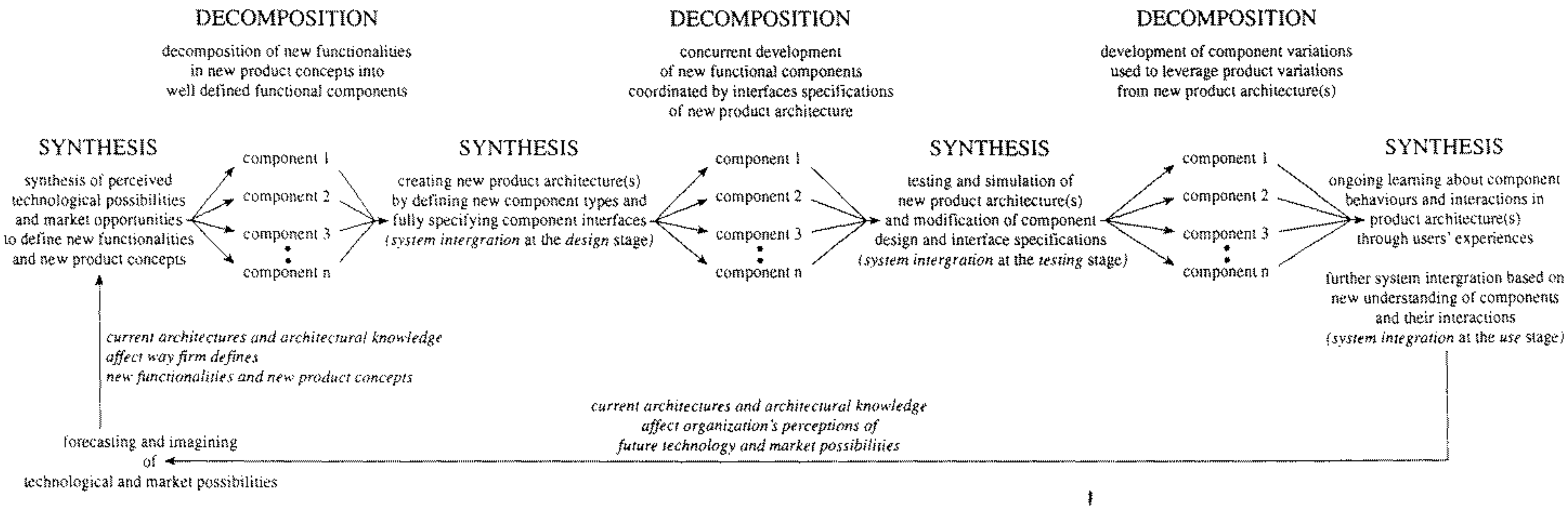
When components conforming to the interface specifications of a new modular product architecture are developed, a further process of synthesis occurs as components are assembled into prototypes and 'beta' versions of products for actual or simulated testing. In this process, architectural learning can occur through discovery, analysis, and resolution of anomalous behaviours during testing and simulation. Such system integration activities during the *testing stage* can lead to modification of the interface specifications of a modular architecture.

As a 'debugged' product architecture is used to leverage product variations into the market, product development may continue through another cycle of decomposition in the form of ongoing development of component variations to support the introduction of new or improved product variations. Learning about component behaviours and interactions in actual use conditions can stimulate further architectural learning and synthesis in the form of refinements to interface specifications in the current modular architecture (or to changes in interface specifications to be incorporated in a next-generation product architecture). The latter activity constitutes ongoing system integration during the *use stage* of an architecture.

Product and process architectures, like any organizational assets, may both enable and constrain an organization's ability to change. Figure 5 therefore also suggests the potential impact of a firm's current architectures on how people in an organization perceive possibilities for future technologies, new market opportunities and new product concepts. This may occur when an organization has adopted an organization design that mirrors its product architectures – for example, by organizing development groups around individual components [19]. In this case, an organizational focus on certain kinds of components may create cognitive blind spots that make it hard for the organization to imagine new kinds of components capable of providing new kinds of functionalities. Thus, a key requirement for managing renewal of an organization's product architectures is institutionalization of processes for regularly and explicitly considering new kinds of functionalities and components that may be incorporated in new product concepts and new kinds of product and process architectures.

Figure 5 suggests that such processes be institutionalized in the first cycle of synthesis of technology possibilities and market opportunities in a firm's long-term architectural planning. In this activity, architects can play a key role in challenging an organization's strategic assumptions about future technologies, markets and product concepts. At the same time, processes may be institutionalized to assure that architects are informed by component specialists of evolving technological possibilities for improving specific components, and that component specialists are aware of possibilities for new product concepts that can suggest directions for development of new kinds of functional components and component technologies.

Figure 5 Alternating cycles of synthesis and decomposition in modular architectural product creation and organizational learning processes



6 New performance measures, incentives, employment relationships and management processes

Using modular architectures to create new products suggests both the possibility – and very likely the need – for new kinds of *performance measures* for assessing the effectiveness of product creation efforts by individuals and teams, for new *incentive designs* to reward good performance at the individual and team level, and perhaps even for new kinds of *employment relationships* that support and encourage good performance by individuals and teams in the long run.

Modular product architectures offer the potential for substantial reductions in the cost, resources and time required to develop new products. In some cases, adoption of processes for creating disciplined modular product and process architectures has reduced resource requirements for product creation by 90% and time to market by as much as 70% [34]. Such gains in efficiency and effectiveness can only be recognized and pursued systematically as a management objective, however, if performance measures are developed to monitor gains in product creation productivity. Architecture-based performance measures are needed for both individual product creation projects and for the overall organization when related architecture creation projects are undertaken. Architectural performance measures likely to prove useful in assessing the effectiveness with which an organization is creating and leveraging its product and process architectures include the ratio of total product creation costs to total revenues, cumulative revenues generated by each product and process architecture, cost savings across product lines resulting from the sharing of common components, intergenerational savings from reuse of existing component designs in next generation architectures, and the like.

When the development of components for modular product and process architectures is carried out through loosely-coupled development activities undertaken by self-managing development groups, the performance of individual component development teams can be directly evaluated, because one component team's performance no longer depends on the performance of another development team. Consequently, it becomes feasible to measure the time, resource, and cost performance of individual component development teams with an accuracy that would not be possible for traditional, tightly-coupled development processes. Accordingly, the feasibility of accurately measuring component development performance makes it possible to establish incentives to reward improved performance by specific component development teams.

Organizations using traditional product development processes typically rely on the tacit knowledge of their development staff and on relatively informal and *ad hoc* processes for managing and documenting interface specifications. The creation of modular product and process architectures, however, requires that an organization make its collective technological knowledge explicit and codify its knowledge of component behaviours and interactions in the form of complete, well documented component interface specifications. Thus, converting from traditional to modular product creation processes requires an organization to establish an employment relationship in which employees are willing to explain and document what they know about component designs and interactions so that this knowledge can be codified, archived and disseminated within the organization. In some cases, employees with critical knowledge may hesitate to articulate their tacit knowledge out of fear that revealing their knowledge may lessen their importance to the organization or, in the worst case, may make the human carrier of the knowledge redundant to the organization.

One approach to managing this potential dilemma in making the knowledge of individual employees explicit is redefining the nature of the knowledge work performed by those employees from a role of maintaining (in tacit form) a particular stock of technology knowledge to managing the flow of new knowledge (in explicit form) into the organization. This dynamic redefinition of the role that key knowledge workers play in the organization can have beneficial effects for both individuals and the organization. Individual knowledge workers become empowered to continue deepening and broadening their own area of expertise. Within this reconceptualization of the way the knowledge worker contributes to the organization, an individual knowledge worker should be less fearful of the potential consequences of explaining what he or she *currently* knows. At the same time, when individuals become managers of explicit knowledge flows rather than guardians of current tacit knowledge stocks, the organization can benefit from the stimulation of learning processes that progressively improve an organization's ability to create new product and process architectures – and thus make the organization more capable of surviving in a dynamic competitive environment.

New knowledge created by development teams should be captured within the organization by documenting and codifying that knowledge. Component development groups in the Chrysler Corporation, for example, are asked to document their analyses and recommendations of alternative component designs in a computer-based 'Book of Knowledge' that can be accessed by other development teams within Chrysler. Similarly, Motorola provides a manual for designing and building flexible pager factories to each team given responsibility for building a new factory. The deliverable for that team, however, is not just the new pager plant, but an amended manual in which the lessons learned by the team in designing and building the new plant have been incorporated into the manual. In this way, when the amended manual is subsequently passed on to the team charged with building Motorola's next factory, the learning of the prior team is transferred to the next team in explicit form. Making an amended manual incorporating team learning a specific deliverable on which the performance of a team will be assessed creates an incentive structure which encourages both team learning and the careful documentation of that learning by teams.

7 Conclusions: towards a new management style for product creation

For many managers, achieving the benefits of creating products through modular architectures will require adoption of a new management style for guiding product creation. In managing modular product creation processes, managers must provide guidance for two essential but distinct processes: 1) defining next-generation and future-generation product and process architectures, and 2) developing product and process variations within current architectures.

In guiding the definition of future product and process architectures, managers should provide visionary strategic management by leading their organization in defining the future product concepts for which the organization will create new architectures. Once future product concepts are chosen, however, managers should not take the role of 'champions' of specific products or of 'heavyweight managers' who push a specific product development project through to completion. Rather, managers should think of themselves as *system designers* whose task is to create organizational systems for the architectural coordination of product creation and realization activities. Those systems must be founded on several key activities and policies in order to implement the new design rules of modular product and process creation:

1 *Integrating long-term technology and market forecasting in a process of planning for next-generation and future-generation product and process architectures.* Defining future generation architectures provides a focus for the integration of technology and marketing forecasts that leads to the identification of future component and component technology requirements, as well as the clarification of specific market information useful in defining future product concepts.

2 *Adhering to a discipline of fully specifying and standardizing component interfaces as a prerequisite to undertaking component development for specific product designs.* Standardizing component interfaces before beginning component development avoids wasteful use of development resources in the reworking of component designs and interfaces – activities that typically consume a major portion of development time and resources when individual component development activities are allowed to drive changes in interface specifications.

3 *Allowing component development processes to become concurrent and self-managing.* Once component interface specifications are fully defined in a modular product architecture, there is little or no need for the traditional development management function of adjudicating interface issues among teams developing interdependent components. Managers new to modular development processes, however, may be uncomfortable *not* intervening in component development processes and letting development groups manage their own work. Managers must learn to focus their attention on the processes of defining product and process architectures, then let component development teams become self-managing in carrying out development processes within those product and process architectures.

4 Requiring that the output of product creation be well defined and codified new organizational knowledge, as well as new products. Strategically important knowledge about markets, technologies, product architectures and components is developed during processes for creating modular product and process architectures. Managers should establish organizational expectations and rewards that encourage the articulation of new knowledge and the architectural codification of that knowledge to make it accessible within the organization. Modular architectures provide a powerful framework for structuring and focusing organizational learning, but using modular architectures to build learning organizations requires that managers also establish processes and incentives for systematically identifying, codifying, and disseminating new knowledge about product and process architectures developed by the organization [29].

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20 A product architecture is related to, but distinct from, the concept of a 'product family' [2]. Some kinds of product architectures – i.e. modular product architectures – enable families of related products to be leveraged from a single architecture, while other kinds of architectures

do not. A modular product architecture is also related to the notion of a technology 'platform'. When a product architecture allows the introduction of technologically improved components (as modular architectures may be designed to do), it provides a 'platform' for leveraging new products based on technological improvements to key functional components.

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33 Product architectures also impact on the strategic value of the three forms of learning that can occur during product creation. Recall von Hippel's [43] finding that complex problem solving processes in organizations create 'sticky information' that is difficult to define precisely or to extract from the 'locus of problem-solving' in which it originated. Problem-solving involving many complexly interdependent variables creates learning that is likely to be highly context-specific – i.e. sticky – and therefore difficult to articulate in more general terms that would enable its application in other contexts. However, to the extent that an organization's problem solving leads to context-specific learning rather than more generalized learning, an organization may tend not to deviate from the contexts in which its 'sticky' knowledge is embedded. Product creation processes in which technological, architectural and component forms of learning are tightly-coupled are therefore likely to generate 'sticky information' whose value as a knowledge resource in other product creation processes may be very difficult to discern, thereby limiting its potential strategic value to an organization [29].

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