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Competing—and Learning—in Modular Markets

Ron Sanchez and Robert P. Collins

This paper explains how the adoption of modular approach product and process architectures can greatly improve product development performance and provide a powerful framework for knowledge management and organisational learning. We first consider specific ways in which modular architectures enable both new processes for product development and new product strategies. We then explain how disciplined adherence to the modular way of creating new products helps an organisation to identify its current technological capabilities more clearly, and to define objectives and processes for strategically focused organisational learning. We discuss three seemingly counterintuitive principles in the new strategic logic of managing in the modular way, as well as new management practices involved in the modular way of working. © 2001 Published by Elsevier Science Ltd

Introduction

In recent years managers in many industries have witnessed broad transformations of their competitive environments. Among the most important of these transformations is an intensification of product market competition that challenges managers to find new ways to increase their firm's product creation capabilities.

In this article, we explain how strategic use of *modular product and process architectures* is now enabling some firms to create greater product variety, to bring technologically-improved products to market more rapidly, *and* to achieve lower costs of product creation and realisation. Drawing on the experience of GE Fanuc Automation,[1] a global leader in industrial automation systems, as well as examples of leading-edge firms in other product markets, we explain how the modular approach to creating products makes possible new kinds of product strategies and is helping firms re-invent the way they compete—and learn—in their product markets.

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Many firms are now beginning to use some aspects of modular architectures in their product strategies, especially in creating “platform” designs for families of products.[2] What is less widely understood, however, is that modular architectures offer a powerful knowledge management framework for identifying a firm’s strategically important knowledge and capabilities and for leveraging them more effectively. When used in this key knowledge management role, modular architectures can help a firm both discover its hidden *capability bottlenecks* and identify its best targets for focused strategic learning and capability development. In addition, modular architectures provide a new means to coordinate and accelerate distributed learning processes within networks of suppliers and collaborating firms. To achieve these benefits, however, firms must set new priorities and adopt new practices in their product creation processes. In effect, managers must learn to follow a *new strategic logic* for competing and learning in modular product markets.

We begin our discussion by explaining one of the most visible benefits of modularity—the ability to configure new product variations quickly and at low cost by “mixing and matching” components within a modular product architecture. We consider both closed-system and open-system strategies for using the configuration flexibility of modular architectures, and explain how modular product strategies are becoming the drivers of new kinds of competitive interactions.[3]

We then draw on the example of GE Fanuc to illustrate some of the key transformations a firm must undergo when adopting modular strategies. We explain how GE Fanuc redefined its product designs as modular architectures, converted its product creation and realisation processes to the modular way of working, and adopted some simple *design rules* for quickly and efficiently leveraging new products from its modular architectures. The result of this transformation was that GE Fanuc reduced its product development time and resource requirements *by more than half,* while significantly increasing the range and number of product variations it offers to customers.

We then consider how a disciplined modular approach to creating product and process architectures can illuminate both the content and structure of a firm’s technological knowledge. We show how modular architectures act as a powerful lens for discovering hidden capability bottlenecks that limit a firm’s ability to create and realise new products. We also explain how some firms such as GE Fanuc are now using modular architectures to coordinate inter-organisational development processes that significantly increase the speed and scope of a firm’s strategic learning. Used in this way, modular architectures provide managers with a powerful knowledge management framework for accelerating development of organisational capabilities.

Obtaining these benefits from modular architectures requires establishing new priorities and new practices in managing the way a firm creates its products and processes. We therefore summarise some basic principles in the new strategic logic for man-

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aging in modular markets—a logic that runs counter to much conventional management wisdom. We consider three fundamental, but at first counterintuitive, principles that managers must master to compete effectively in modular markets:

- Products design organisations.
- Standardisation increases flexibility.
- Discipline enhances creativity.

We conclude by noting two ways that modular architectures can help managers maintain a clear focus on the critical tasks of setting strategic directions and goals for their firms.

How modular architectures change product competition

Every product has an *architecture*, which is defined by two fundamental properties of a product design:

- The *decomposition* of the overall functionalities of a product (i.e., the set of benefits that the product will bring to its users) into the specific *functional components* that make up the technical structure of the product.
- The *interface specifications* that define how the various functional components will *interact* with each other when they function together in the product.

The functional decomposition of an architecture is usually most visible in assembled products, such as desktop computers that are composed of distinct components such as microprocessors, memory chips, and disk drives. However, virtually all product designs can be decomposed into functional components or elements that interact in specifiable ways. A simple plastic cup, for example, can be decomposed into rim, wall and base, and each of these components must interact with the others in specified ways within the product design. Service products can also be decomposed architecturally into *activity* components. Retail banking services, for example, are composed of routines for making deposits, transferring funds, providing overdraft protection, and so on, and each routine must interact with the other routines in specified ways to provide each customer with a "seamless" banking service.

A product architecture becomes *modular* when:

- Interfaces between functional components are specified to allow *variations in components* to be substituted into the product architecture;
- Interface specifications are then *standardised*—that is, not allowed to change during the commercial lifetime of the product.

Most personal computers have modular architectures that accept variations in components (such as disk drives or memory boards of different capacities) as long as each variation conforms to the standardised interface specifications for that type of component. Standardising interfaces that allow substitutability of component variations lets a firm "mix and match" component variations in a modular architecture to configure product variations that offer different combinations of component-based functions, features, and performance levels.[4]

In creating modular architectures, firms may pursue either *closed-system* or *open-system* strategies. In a closed-system strategy, a firm creates a proprietary modular architecture intended to accommodate only component variations supplied by the firm. In an open-system strategy, a firm may disclose its interface specifications so that other firms can develop components for its product architecture. Alternatively, a firm may collaborate with other firms in establishing *industry standards* that define the types of functional components they will use and the interface specifications that will apply to each type of component.[5]

Adopting a modular architecture is a watershed event for both a firm and an industry, because it creates a well-defined and relatively stable technical infrastructure that encourages firms and their suppliers to develop component variations compatible with the architecture. Firms that create new products can then draw on a growing array of new and improved modular components in configuring a stream of product variations. Moreover, when competition among suppliers of standard components drives component prices down, costs of products also fall.

The flexibility to leverage new products by configuring new combinations of components within a modular architecture makes possible a number of new product strategy initiatives:

- Modular architectures can be used to explore customer preferences for different combinations of functions, features and performance levels through *real-time market research*.[6] Sony, a skilled user of modular architectures, leverages many variations of its products to discover "in real time" the most desired models in each of its markets. In developing the US market for its Walkman products, Sony introduced more than 160 product models in a ten-year period to discover the combinations of functions, features, performance levels, and price most preferred by US consumers.[7]
- Modular product variations may be leveraged to saturate the most profitable regions of product space and leave no uncontested product space to invite entry by competitors. This strategy has helped Sony maintain a dominant global market share in Walkman-type products.[8]
- To maintain market leadership, interfaces in modular architectures may be specified to accommodate new or improved components expected to become available during the commercial lifetime of the architecture. Improved products can then be configured and brought to market as soon as improved components are developed. Sony used this modular

strategy to introduce its HandyCam video cameras, offering a rapid succession of upgraded models based on planned improvements in key components.

- When a modular architecture is strategically partitioned so that product variety and change is "contained" in specific components, other components may be standardised and used in all or many of the product variations leveraged from a modular architecture. Effective use of standardised "common components" may significantly reduce costs of developing, producing, inventorying, and servicing allowing substantial cost reductions while sustaining high levels of product variety. Today Volkswagen leverages six well differentiated product lines from its "A4" platform architecture,[9] while achieving substantial cost savings by using sets of non-differentiating common components in all models.

Firms that understand how to use modular architectures in such ways may launch aggressive new product strategies that create new competitive dynamics in an industry. Product variety increases, technologically upgraded products come to market more quickly, *and* product costs (and prices) decline. Product markets as diverse as personal computers, consumer electronics, mobile phones, home appliances, power tools, sports bicycles, athletic shoes, and financial services are now showing the competitive effects of the increasing modularisation of products.[10] (See the Appendix for a summary of recent research on modular architectures and their roles in product and organisation strategies.)

Successfully pursuing modular product strategies, however, requires new processes for creating and realising products. We therefore next consider GE Fanuc's experiences in converting to modular product architectures and in creating modular process architectures to support its modular product strategies.

Reinventing product creation at GE Fanuc Automation

GE Fanuc Automation produces industrial automation systems that can be individually configured to control a great variety of production processes. As factories around the world began to modernise and automate in the 1980s and 1990s, demand for customised automation systems increased sharply, automation technologies advanced rapidly, and competition intensified as several major firms entered the market. These developments challenged GE Fanuc to find new ways to expand its range of products, increase its speed of bringing technologically improved products to market, and reduce the costs of its products.

GE Fanuc's first step was one taken by many firms in the 1980s—replacing a traditional sequential product development process with a multifunctional team approach. This change reduced GE Fanuc's product development cycle from about 30 months to 20 months, but as other firms in the industry also adopted team-based development processes and reduced their development times, the window of opportunity for profitable sales of new generation products narrowed to a few months or less. Extensive efforts by GE Fanuc's development teams to achieve further time reductions were not successful. Adding more people to development projects, for example, seemed only to *increase* the time required to complete a project.

GE Fanuc's managers eventually realised that achieving further reductions in development time would require a fundamentally new approach, and so they decided to "go back to the drawing boards" to rethink the way the firm developed new products. Their first step was to assemble a task force to analyse in detail several recent development projects to determine exactly how time and resources were being consumed.

The task force's analysis led to a startling discovery that brought into sharp focus a key relationship between product architectures and product development cycle times. The analysis showed that designs of key components were frequently changed during development projects to accommodate new market demands or to incorporate new technologies. Making design changes in one component, usually required changing the designs of other components that the component interacts with, which in turn led to changes in the designs of yet other components, and so on, in effect causing "chain reactions" of time-consuming redesigns of components and respecifications of the interfaces between those components. The task force found that such chain reactions of component redesigns occurred many times during a development project and typically consumed *more than half of the time and resources* required to develop a new product. Moreover, because the interfaces between components were evolving in uncontrolled ways as components were being redesigned, both the component designs and the interface specifications that emerged from each development project were unique to that project. By trying to use this traditional development process to respond to increasing market demands for more product variety, the firm was not only slow in bringing new products to market, it was also creating a costly and rapidly growing number of idiosyncratic components and parts that could only be used in one product model.

This analysis persuaded GE Fanuc's managers that a much more disciplined approach to managing component designs and interface specifications was the key to achieving major reductions of time, resources, and overall costs in developing new products. GE Fanuc's managers also began to understand that better coordination of component designs and interface specifications across the firm's development projects was the key to increasing the use of common components and lowering product costs.

GE Fanuc's managers subsequently adopted three new practices in their development processes:

(i) GE Fanuc adopted a standardised way of decomposing its product architectures into key functional components, which the firm calls *technology building blocks.* Figure 1 shows the standard types of components that make up the technology building blocks in a typical GE Fanuc product architecture.

(ii) When developing a new product architecture, GE Fanuc first defines “flexible” component interface specifications that allow a range of component variations within each technology building block to be combined with a range of component variations in other technology building blocks to configure a large number of product variations.[11]

(iii) GE Fanuc also follows a strict policy of “freezing” the interface specifications between technology building blocks *at the beginning* of component development processes. In effect, GE Fanuc constrains the subsequent development of new components to conform to interface specifications that have been standardised for each technology building

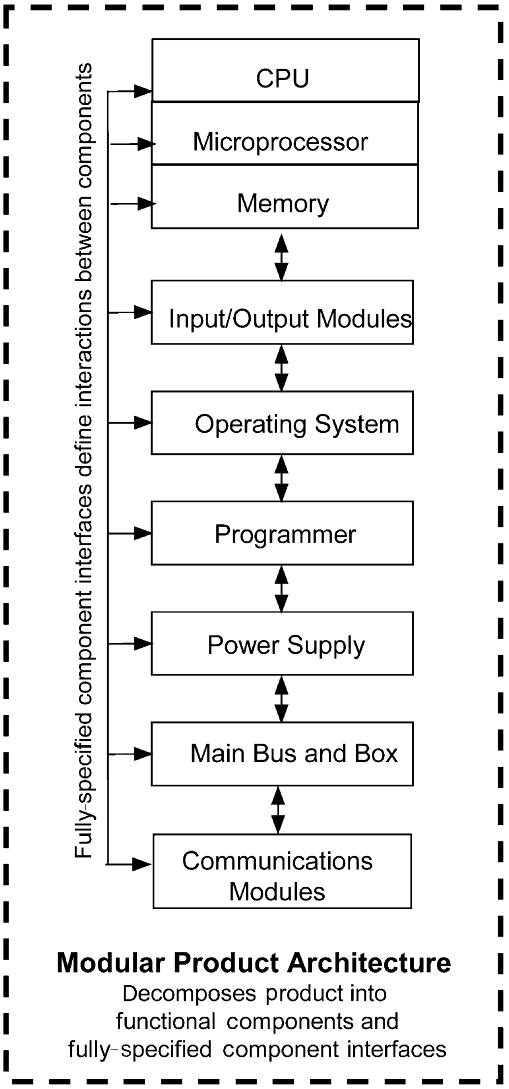

Figure 1. The Technology Building Bocks in GE Fanuc’s Modular Product Architecture

block. The standardised interface specifications for each of the firm's product architectures are then compiled in "interface documents" that are provided to both internal and external development groups.

Following adoption of these practices in GE Fanuc, time-consuming chain reactions of component redesigns were eliminated, because all component designs must now conform to a stable set of standardised interface specifications. Eliminating component redesigns significantly reduced the amount of development resources consumed. Moreover, because component designs must conform to a stable set of interface specifications, components can now be developed *concurrently*. As a result, development cycle times have been greatly reduced. Once fully implemented, this modular approach to managing product creation reduced GE Fanuc's time to bring a new product architecture to market to an average of *6 to 9 months*, compared with 20 months under its earlier process.

GE Fanuc's greatly improved speed in developing new products now lets the firm "fast cycle" through development of several new product architectures in the time previously required to develop a single new product. GE Fanuc now uses this fast-cycle capability to renew its product lines more frequently and to bring technologically improved products to market more quickly. By sharing its standard component interface specifications with component suppliers, GE Fanuc has access to an expanding range of available component variations that lets the firm configure a virtually unlimited number of product variations to meet individual customer requirements. Further, the firm's component interface specifications are now strategically coordinated to enable the use of certain common components across product models and even across product architectures, leading to sharply lower costs for many key components.

Applying modularity principles to process architectures

As GE Fanuc began to use the flexibilities of its modular product architectures to introduce more new products more quickly in the 1990s, managers began to understand the importance of developing complementary flexibilities in the firm's process capabilities. Reasoning that designs of processes could also be decomposed architecturally into "component" activities that interact in specifiable ways, GE Fanuc's managers defined the basic building blocks in the firm's product creation and realisation processes. As shown in Figure 2, managers identified design, manufacturing, and user capabilities as the key technology building blocks in GE Fanuc's process architecture. Staff then spent several months defining the specific capabilities available to the firm in each technology building block.

GE Fanuc's next step was to define process interface specifications governing the interactions of the technology building

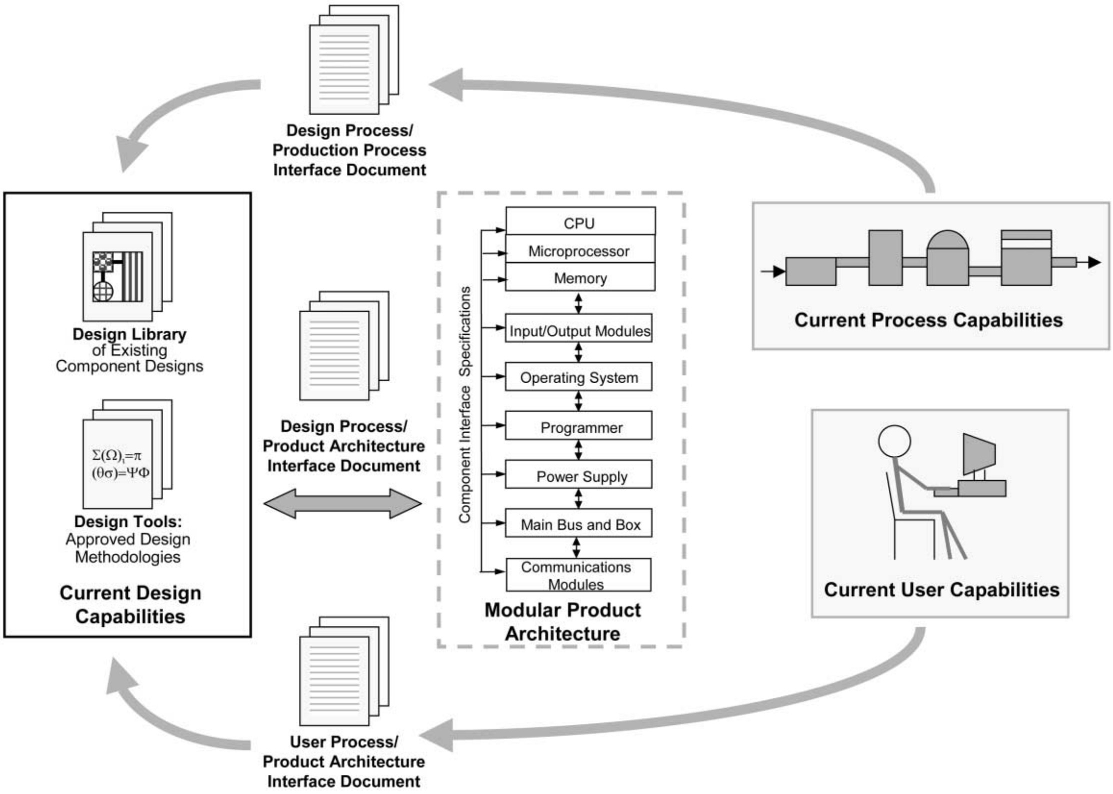

Figure 2. The Technology Building Blocks in GE Fanuc's Modular Process Architecture

blocks in its process architecture. Like its interface specifications for products, these process interface specifications are compiled in "process interface documents" that are disseminated throughout the firm. As suggested in Figure 2, GE Fanuc's process interface documents contain both technical specifications defining the current capabilities in each process technology building block and certain "design rules" governing the interactions between the firm's product architectures and the design, production, and user capabilities in its process architectures. Let us take a closer look inside each of these process interface documents.

The Design Process/Product Architecture Interface Document defines the current design capabilities of the firm and provides design rules governing how those capabilities may be used in creating and leveraging product architectures. The current capabilities in GE Fanuc's design technology building block are defined by (i) a "design library" of currently available designs for parts and components that are compatible with one or more of the firm's product architectures, and (ii) a set of "design tools" (design methodologies) that GE Fanuc's developers must use in designing new parts and components. To assure that its current design capabilities are used quickly and efficiently, a basic design rule adopted by the firm requires developers to re-use an existing component in the design library whenever it can provide the performance required for a new product. If no suitable component design is available in the design library, then a second design rule requires developers to create a new component design by following an existing design methodology in the current set of tools. Following these two design rules assures that GE Fanuc's developers will not waste development time "re-inventing the wheel" by inventing new component designs or design methodologies when existing designs and methodologies can do the job.

The Design Process/Production Process Interface Document gives designers detailed definitions of current production capabilities of the firm and its key suppliers. In defining the internal and supplier capabilities included in its production technology building block, GE Fanuc's managers went well beyond simply compiling general descriptions of production capabilities. Rather, the firm defined precisely the limitations in each production capability that impose constraints on the components the firm can make and assemble. The firm's production capability in assembling printed circuit boards (PCBs), for example, is defined by the maximum and minimum dimensions of PCBs that can be processed through GE Fanuc's or its suppliers' assembly lines, by current limitations in component sizes and pin spacings the firm or its suppliers can mount on a PCB, and so on. In effect, clearly defining the *constraints* that available production capabilities impose on the products the firm can make has enabled GE Fanuc's managers to understand clearly the actual flexibilities that the firm currently has to operate within those constraints.

To assure that new product variations that designers want to leverage from GE Fanuc's modular product architectures can be readily manufactured, the Design Process/Production Process Interface Document also includes a design rule that requires designers to select or create component designs that the firm and its suppliers are currently capable of producing.

A similar approach was followed in defining GE Fanuc's user capabilities technology building block. GE Fanuc's automation systems are monitored by human operators who have been trained to recognise a number of Windows-based templates and icons displayed on computer monitors to represent various production processes. These templates and icons are now compiled in the Design Process/User Process Interface Document to represent current user capabilities. A design rule requires that existing templates and icons be re-used wherever possible in new product designs, because introducing new templates or icons imposes significant costs of providing additional training to large numbers of operators.

Defining the capabilities in its process architecture and coordinating the interactions of its product and process architectures through clear design rules has enabled GE Fanuc to become as fast in producing and installing new products as it is in developing them. When new products are designed to be manufactured within current production capabilities, for example, newly developed products can go into full production in a matter of days, not months. When a new product architecture does require new process capabilities, however, those capabilities can be defined *before* development of product components begins.

This early definition of new process capability requirements enables concurrent development of both new product components and the new process capabilities needed to make and assemble new components.

Using modular architectures to manage knowledge and strategic learning

As GE Fanuc's managers implemented their modular approach to product creation, they began to understand another important benefit of modular architectures. Well-defined modular architectures provide a powerful framework for identifying and leveraging a firm's current knowledge, for discovering hidden "capability bottlenecks", and for extending and accelerating strategic learning processes. Let us examine each of these important benefits.

Most firms lack a systematic framework for identifying knowledge that is currently "inside" a firm or available to it. Consequently, to determine whether a firm has the knowledge needed to commercialise a new product idea, managers must typically obtain feasibility assessments from various technical experts within the firm. The process of assessing feasibility is time-consuming, but more importantly, such assessments are frequently performed under considerable time pressures and often produce incomplete or inaccurate assessments. The consequences are that firms sometimes do not undertake development projects they could readily complete, or—more critically—they sometimes commit to projects they actually do not have the know-how to complete.

As GE Fanuc came to understand, clearly defining both the components currently available in its design library and the design tools currently available to component developers creates a "balance sheet" of the firm's current design capabilities. New product ideas, once decomposed into sets of required components, can be quickly compared against the balance sheet to determine which needed components the firm already has or could readily design, and which components would require new designs or new design methodologies. Similarly, defining its current production and user capabilities enables GE Fanuc to recognise which new product ideas would require developing new production or user capabilities, and which would not. Thus, in a fundamental sense, GE Fanuc's careful architectural definition of its current product and process capabilities enables its managers to "know what we know"—and therefore to leverage the firm's current knowledge more effectively.

Equally as important, GE Fanuc's managers can also recognise when new product ideas would require capabilities the firm does *not* currently have. In effect, the careful definition of capabilities involved in creating modular product and process architectures brings to the surface the hidden "capability bottlenecks" that limit a firm's ability to design, produce, and support new products. The capability bottlenecks that are currently limiting a firm's options for creating new products can then be targeted for focused strategic learning and capability development. GE Fanuc now uses this method to generate an evolving "Wish List" of well-defined capabilities that the firm wished it had, because they would open up significant new market opportunities for the firm. The Wish List is carefully and frequently reviewed by GE Fanuc's senior and mid-level managers to select opportunities for strategic investments in developing important new capabilities.

GE Fanuc's modular architectures also help the firm to develop more finely-tuned approaches to managing its strategic learning and capability development. For each of the technology building blocks in its modular product architectures, GE Fanuc pursues a specific strategy for developing and sourcing components. Certain components (like memory chips) are technically necessary, but are not sources of distinctive performance in the firm's products, and the firm simply buys the most cost-effective components currently available in the market. Components like microprocessors and operating systems, however, are important performance drivers in GE Fanuc's products. Microprocessor design is not a capability in which the firm believes it could be a world leader, so GE Fanuc works with world-class microprocessor firms as strategic partners in developing new microprocessor designs for its products. However, GE Fanuc does have world-class capabilities in developing operating systems and programmers for the sensors and controls used in industrial automation systems. GE Fanuc therefore develops these technology building blocks internally as a key source of strategic competitive advantage. GE Fanuc pursues similar strategies for developing the technology building blocks in its process architectures.

GE Fanuc also uses its modular architectures to stimulate and coordinate globally distributed, inter-organisational learning processes. Because interface specifications for modular architectures define the essential *outputs* of component development processes (i.e., component designs that conform to standardised interface specifications), developing components for a modular architecture can become a "loosely coupled" process carried out autonomously and concurrently by competent development groups anywhere in the world. By publishing the interface specifications for components in its modular architectures, GE Fanuc now benefits from the activities of more than 300 firms worldwide that develop components compatible with GE Fanuc's product architectures. The growing range of component variations compatible with the firm's modular architectures greatly enhances GE Fanuc's ability to configure customised automation systems to serve every customer's requirements.

A few firms such as GE Fanuc have realised that modularity offers more than product strategies. Modular architectures are also a foundation for learning organisations that can quickly adopt the most advantageous combinations of internal, collaborative and market arrangements for developing and sourcing new components and capabilities. It is no coincidence that firms in industries with the highest sustained rates of technological progress—e.g., semiconductors, personal computers, and telecommunications equipment—are also the most extensive users of modular architectures.[12]

New management roles in modular approaches to product creation

Modular approaches to managing product creation also differ from traditional approaches in the roles that managers play and the kind of technological learning that occurs in each approach, as suggested in Figure 3.

Traditional product development typically requires initial inputs from product line managers to agree on the general performance attributes and cost characteristics desired for a new product. Given a statement of these goals for a new product, developers first create a system design that decomposes the new product into subsystems and components. As we have discussed earlier, interface specifications typically change frequently as new component designs are developed, and the lack of stable component interfaces during development processes leads to chain reactions of component redesigns. These chain reactions mean that mid-level managers must frequently adjudicate a variety of

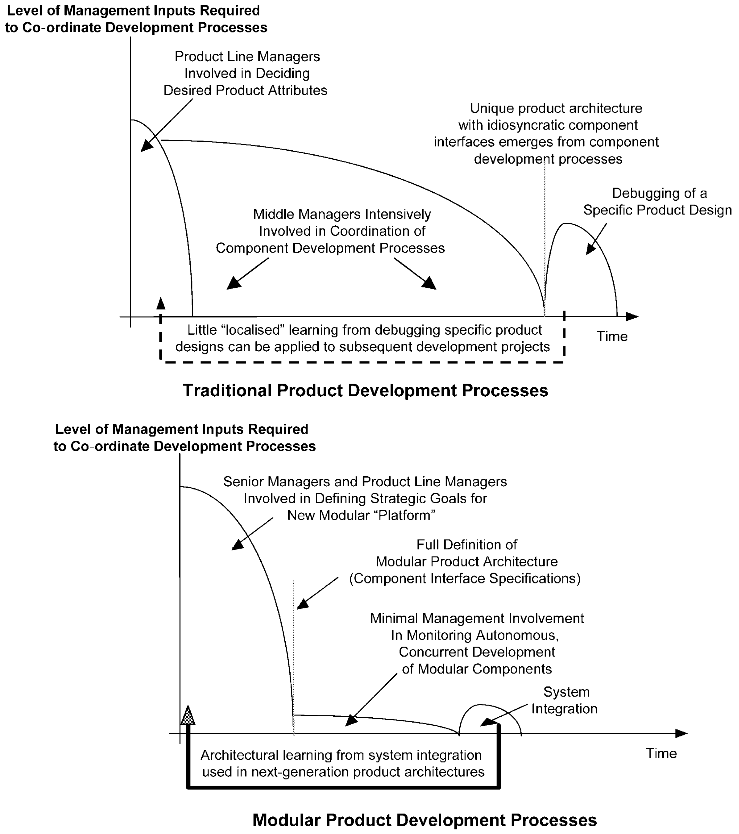

Figure 3. Comparison of Management Inputs and Organisational learning in traditional versus Modular Product Development Processes

"interface issues" arising between component development groups.

Interface issues take several familiar forms. For example, when one component development group requests a change in a second group's component design that is needed to help the first component work better in the overall product design, the second development group may not agree with the intent of the requested design change. Managers will then have to intervene to decide whether a component design change should be made. If a design change is to be made, managers may have to ensure that each development group cooperates fully in making design changes, and may have to decide how the costs of redesign will be allocated to each development group. Moreover, if a component development group has gone on to another development project, managers may have to decide whether a needed component redesign should receive priority over the group's current design project. As GE Fanuc found in analysing its traditional development processes, such decisions can consume very significant amounts of middle management time, as suggested in Figure 3.

By contrast, the modular approach to product development must be initiated with a higher level of inputs from top management, because the objective of the modular development process is to create a "platform" for the firm's strategic initiatives in a given product market over a strategically determined time horizon—often two or three years or longer. Thus, a higher level of participation by top management is needed to provide strategic guidance in defining the extent of market coverage and the rate of technological upgrading desired from a new product architecture. These strategic inputs from top management then set the goals for the specification and standardisation of component interfaces that will "design into" the product architecture the desired strategic flexibility to leverage and upgrade products.

When fully specified and standardised, the interface specifications for a new modular product architecture provide an *information structure* that implicitly coordinates each component development group's activities. As long as all development groups design components that conform to the standardised interface specifications of the modular architecture for their component, middle managers no longer need to adjudicate interface issues during development, because interface issues no longer arise. The time that middle managers spend managing component development processes can be greatly reduced and largely directed to checking whether individual component development groups are staying on schedule and within budget.

Throughout the modular development process, both top and middle levels of management have a critical role to play in ensuring that all component development groups agree to a set of standardised component interfaces for a modular architecture—and then strictly conform to those interfaces in creating their component designs. As firms that have worked with modular development processes have learned (many of them the hard way!), discipline by all component development groups in sticking to the standardised interface specifications is the key to radically reducing development time through concurrent component development.

New approaches to managing interface specifications also play a critical role in the technological learning that occurs in modular development processes. Because interface specifications change frequently during traditional development processes, component developers tend to take a very pragmatic, problem-solving approach and specify interfaces that are simply adequate for specific components at their current state of development. A similar pragmatic approach is also likely in finalising interface specifications after debugging a newly developed product. When developers manage interface specifications in this ad hoc way, they often fail to develop in-depth systematic understanding about the ways that different types of components can reliably interact in product architectures. Thus, traditional product development often results in “spotty” technological knowledge limited to specific component designs.[13]

Creating modular product architectures, however, leads developers to acquire much more systematic architectural knowledge about how various components work and interact. An analogy from just-in-time (JIT) manufacturing suggests why. The discipline of running a lean JIT production system in which all processes are expected to work right all the time helps a firm quickly discover and solve problems in producing parts that would be obscured if the firm maintained “buffer inventories” of parts. Analogously, the discipline of fully specifying component interfaces that are expected to work perfectly for a range of component variations in a new modular product architecture encourages developers to discover and diagnose deficiencies in their knowledge of how such components systematically behave and interact. Such deficiencies in a firm’s architectural knowledge are usually obscured in the traditional development process by the “process buffer” of allowing frequent ad hoc changes in interface specifications.

Architectural learning about components is also fostered when a firm uses *system integration* methods to debug a new modular product architecture. In systems integration, component interactions are analysed and tested for all combinations of component variations allowed by the modular architecture to develop insights into the “system behaviours” of the various types of components. These insights can then be incorporated in new or improved interface specificationsfor governing the interactions of components in a firm’s product architectures. When a firm adopts the further discipline of regularly translating its architectural learning into improved interface specifications, the firm’s interface documents become both an archive and a balance sheet of the firm’s technological knowledge about the building blocks of its products and processes.

A new strategic logic for competing in modular markets

Managers interested in applying modularity concepts in their firms must learn a new strategic logic for competing that contradicts much conventional management wisdom. The strategic logic of modular architectures is based on some new "first principles" of organising and managing that at first seem counterintuitive. We now briefly consider three principles in the new strategic logic of modular markets.[14]

"Products design organisations"

Implicit in the design of every product are specific tasks that must be performed in order to develop and realise that product. As a result, the product designs a firm creates greatly influence how the organisation designs the firm could adopt to develop, produce, distribute, and service its products. When the component designs in a product architecture are complexly interdependent, processes for creating and realising components will also be complexly interdependent and must be organised to support frequent communication, coordination and other interactions. By contrast, when interface specifications are standardised in a modular architecture, component designs that conform to those interface specifications become "loosely coupled," in the sense that various component designs can be freely interchanged in the product architecture. Processes for creating and realising those components can then also become loosely coupled—i.e., they become largely autonomous and do not require frequent communication and coordination between component development groups. In this sense, at a fundamental level, "products design organisations".[15]

The implications of this principle for strategic managers are profound. In essence, the principle tells us that making a firm's processes and structures more flexible and "modular" requires as *an essential first step* making the firm's product architectures more modular. Without adopting flexible modular product architectures, the goal of creating flexible modular organisations will remain an elusive dream.

"Standardisation increases flexibility"

Standardising components and interactions at a lower level of a system is the key to creating important forms of flexibility in a higher level of the system. For example, standardising the basic goods and services required to travel by automobile brings flexibility to the "higher level" process of taking automobile trips. Just imagine how difficult and time-consuming travelling by car would be without standardisation of gasoline types, gas pump nozzle sizes, lubricant types, tyre sizes, types of highway signs, traffic rules requiring cars to stay on one side of the road, and so on.

Analogously, if the functions and interactions of components in a new product architecture are not standardised, developing the new product architecture becomes complex, difficult and time-consuming. Standardising component types and interfaces, however, greatly reduces the time, cost, and difficulty—or in other words, increases the *flexibility*—of processes for developing new product architectures.

"Discipline enhances creativity"

Creativity is often assumed to require an environment with unfettered freedom to explore and experiment. Yet as we have suggested here, a firm's creativity in developing new products can be greatly enhanced by following some well-defined *rules for creating.* These rules occur in two forms, each governing a different level of creative activity.

One form of creativity consists of combining things (components or activities) in new ways that are permitted by a current set of *combinatorial rules.* For example, blues musicians often improvise new "riffs" or patterns of notes within the traditional structure of chords and progressions—i.e., the combinatorial rules—that define blues as a form of music.

A second form of creativity consists of creating new sets of combinatorial rules that bring new possibilities for improvising. For example, jazz has evolved from a fairly narrow set of early musical patterns—i.e., combinatorial rules—to the much broader and more highly elaborated sets of chords, progressions, and beats that now characterise modern jazz as a form of music. Analysis of the evolution of the combinatorial rules that define jazz reveals both the ongoing adaptation and incorporation of "components" borrowed from other music forms and the invention of new musical components, as well as experimentation with new ways of combining components. In other words, in emerging as a new form of music, jazz has explored a number of *transformative rules* for creating new combinatorial rules for interrelating music structures and components.

In the same way, the creation of new products can flourish by following both combinatorial and transformative rules for creating. When a firm creates a modular product architecture, the interface specifications for the architecture provide a set of combinatorial rules within which developers can freely improvise new products based on new combinations of modular components. Of course, firms also need to be creative by "thinking outside the box" and periodically going beyond the combinatorial possibilities of their current architectures. It is impossible to recognise what constitutes "outside the box" thinking, however, if you can't tell what, in effect, is already "inside" the boundaries of the box. When a firm's managers can clearly understand the combinatorial limits inherent in the interface specifications of its modular architectures, it becomes much easier to recognise or imagine next generation architectures that would represent significant transformations beyond the current capabilities of the firm.

Contrary to the popular notion of unfettered freedom as the cradle of creativity, discipline in exploiting the combinatorial possibilities of a current modular architecture and in defining transformative modular architectures with new combinatorial possibilities may well be the more productive—and more manageable—engine of creativity. One of the greatest strategic benefits of modularity, therefore, may be providing clear rules for managing both *creative improvisation* within an organisation's current capabilities and *creative transformations* to new sets of organisational capabilities.

Conclusion

The complexity and dynamics of contemporary business environments challenge all managers to find new frameworks for making sense of competitive environments and for identifying each firm's strategic options for action. We therefore conclude our discussion of modularity by suggesting a further—and perhaps the most important—benefit that modularity can bring to the managers of a firm.

Traditionally, firms have developed individual products, and for most firms today the units of strategic analysis and planning remain the individual products they offer to markets. Yet today the rate of change in most product markets is so great, and the breadth of product variety needed to meet customer demands is so broad, that focusing management attention on individual products can lead to overwhelming complexity. For managers trying to understand the scope and speed that a firm must sustain in creating new products for its markets, thinking in terms of individual products may no longer be the most appropriate—or even feasible—way to grasp a firm's strategic options for approaching markets. Today, managers who think in terms of individual products may fail to see the "forest" because of their focus on the "trees".

Modular architectures, by contrast, are strategic platforms for leveraging a range of product variations and for managing planned technological upgrading of products over time. Usually a significant part of a market can be served—often for an extended period of time—by a well conceived and well executed modular architecture. Modular architectures therefore provide a new unit of strategic analysis and planning that encompasses a potentially wide range of individual products. As many senior managers in companies that have adopted modular architectures have realised, thinking in terms of modular platforms rather than individual products can significantly reduce the complexity managers face and bring into focus the broader and longer-term view of products and markets that managers must have.

Further, when the standardised interfaces in modular architectures are used to coordinate product creation and realisation processes, those processes can become largely self-managing. Both mid-level and senior managers can then redirect much of their time and attention from the routine tasks of monitoring, problem solving and intervention in those processes to refocus on the essential tasks of strategic direction-setting and goal-setting.

In the final analysis, the greatest benefit for the managers of a firm that adopts the modular way of working may well be a greatly improved ability to see the firm's strategic options more broadly and clearly—and to reclaim the time needed to provide vision and leadership in pursuing those options most effectively.

Appendix. Recent research on modular architectures

Economists were among the first researchers to study the impact of product architectures on competition. Several industrial organisation economists[16] have investigated the competitive implications of adopting standardised interfaces between products (and by extension, standardised interfaces between components in products). The institutional economists Langlois and Robertson[17] also documented the key role of standardised modular interfaces between components in stimulating high rates of innovation in the personal computer and consumer electronics industries.

Strategic management researchers began to investigate the competitive consequences of modularisation of product architectures in the 1990s. Garud and Kumaraswamy[18] investigated the use of modular architectures to achieve *economies of substitution*—the cost savings that result when component variations can be "substituted" into a product design to create new product variations at low cost. Sanchez and Sudharshan analysed the enabling role of modular architectures in the real time market research—the use of modular architectures to leverage product variations used to explore markets in real time through fast, low-cost leveraging of modular product variations.

The use of architectures to manage interactions of product and process designs began to be researched in the 1990s. For, example, Shirley[19], Ulrich,[20] and Robertson and Ulrich[21] explored a number of ways in which product architectures can be used to improve coordination of a firm's new product designs and its manufacturing processes.

Some key implications of modularity for strategic management began to emerge in the mid-1990s. Sanchez[22] explained how modular architectures can be the basis for creating significant new *strategic flexibilities* that enable firms to bring a broader range of products to market more quickly, to upgrade their products more frequently, and to create new products at lower costs of development. Sanderson and Uzumeri[23] documented Sony's use of modular product architectures to manage *families* of consumer electronics products such as the Walkman. Sanchez[24] subsequently analysed the considerable changes in the *marketing processes* of firms that are possible when they can use modular product and process architectures to leverage large numbers of product variations.

Some broad organisational implications of modularity were suggested by Sanchez and Mahoney[25] in their research into the role of modular architectures in creating more flexible organisation designs and more effective processes for organisational learning and innovation. Meyer and Utterback[26] and Meyer, Tertzakian and Utterback[27] have explored the ways in which architectures can help identify strategically important capabilities and define objectives for more focused research and development. Research into the impacts of standard modular architectures on technology-intensive organisations and technical workers has been undertaken by Tushman and Murmann[28] and Wade[29], among others. Sanchez[30] described new kinds of product development processes and new allocations of development tasks that organisations need to adopt when they begin to use modular architectures. Baldwin and Clark[31] have drawn on their historical studies of the computer industry to suggest some general implications of modular architectures for the management of product development and market strategies.

The broader technological, organisational, and strategic impacts of modular architectures are now being elaborated by growing numbers of management researchers. Schilling has proposed a general theory of modular systems and the incentives that give rise to modular systems in a product market. Drawing on his studies of firms that are now making the conversion to the modular way of working, Sanchez (forthcoming)[32] explains how modular architectures can serve as a comprehensive framework for integrating technology strategy, product strategy, organisation strategy and organisational learning.

References

1. GE Fanuc Automation is a joint venture of General Electric Company of the US and Fanuc of Japan, and is managed as a GE company. As Chief Executive Officer, Robert P. “Bob” Collins led GE Fanuc Automation during its adoption and implementation of the modular architectural approach to creating products in the late 1980s and 1990s. During this time, GE Fanuc became a global leader in industrial automation systems and today provides automation equipment and support services to leading corporations around the world. Collins recently retired from GE Fanuc Automation and is now head of Capstone Partners, a consultancy in executive leadership for organisational transformation and improvement of value-creation capabilities.
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4. Sony's "mixing and matching" of components in modular architectures for the Walkman and other product families is discussed in S.W. Sanderson and M. Uzumeri, *Managing Product Families*, Irwin, Chicago (1997).
5. In some cases, the product architecture of a dominant firm may establish a de facto industry standard architecture, much as Intel's Pentium microprocessors defined the de facto standard architecture of personal computers in the 1990s.
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7. Sanderson and Uzumeri (1997) (see Reference 4).
8. Meyer and Utterback (1993) (see Reference 2).
9. The Volkswagen Golf and New Beetle, the Audi A3 and TT, and several Seat and Skoda models are based on Volkswagen's "A4" platform architecture.
10. Examples of modular architectures in these industries are discussed in Sanchez (1999) (see Reference 3).
11. The power of modularity to leverage large numbers of component variations can be illustrated with the simple example of a 10-component product with 10 available variations for each type of component. This modular architecture can leverage 1010=10,000,000,000 individual product variations. See Sanchez (1999) (see Reference 3) for a general foundation of the ability of modular architectures to leverage product variations.
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