Building real modularity competence in automotive design, development, production, and after-service

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Abstract: In recent years, modular approaches to design and production have been discussed and implemented in various ways in the automotive industry. However, this paper draws on the author's extensive work with firms in the automotive and other industries to suggest that there is still relatively limited understanding of what modular strategies really mean and of what effective implementation of modularity strategies would entail in the automotive industry – with the result that at least some automotive firms that claim to be using modular strategies are in fact doing so in name only. This paper then proposes the essential principles on which effective implementation of modular strategies depends in any industry. We illustrate these principles with examples of both effective and faulty modularity practice from the automotive and other industries. We then propose a modularity maturity model for assessing the degree to which a firm has developed and is applying a real modularity competence in automotive design, development, production, and after-service.

Keywords: action research; modularity; competence; modular architectures; product development.

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1 Introduction

Modularity has been used for several decades as an engineering design technique in many industries, including the automotive industry. However, in the 1990s some researchers in strategic management and technology strategy began to suggest that modularity could be much more than an engineering design technique. Initially drawing on examples from industries like computers and consumer electronics, these researchers (including this author) began to suggest that modularity could in fact become the basis for entirely new kinds of product strategies, organisation structures, and business processes (Garud and Kumaraswamy, 1993, 1995; Langlois and Robertson, 1992; Sanchez and Sudharshan, 1993; Sanchez, 1995a, 1996; Sanchez and Mahoney, 1996; Sanderson and Uzumeri, 1997).

In the late 1990s and 2000s, increasing numbers of studies in different industries began to gather convincing evidence that effective *strategic uses* of modularity could substantially improve a firm's ability to offer increased product variety, significantly improve speed to market, enable more rapid technological upgrading of products, *and* radically reduce costs for design, development, production, and servicing of products (Funk, 2008; Sanchez, 2002a, 2002c, 2004a, 2008; Sanchez and Collins 2001; Asan et al., 2008; Worren et al., 2002).

Since the 1990s, modular strategies have clearly become the *dominant logic* (Prahalad and Bettis 1986) for competing in electronics, software, and many assembled products industries, and firms using modular strategies with varying levels of sophistication and competence are now evident in many kinds of industries (see endnote 6). The automotive industry has also joined the 'movement to modularity', and in recent years various approaches to modular design and production have been implemented by a number of firms in the automotive industry.

This paper suggests, however, that in spite of the effective strategic use of modularity by a few automotive firms, in the automotive industry generally there is still comparatively limited understanding of what modular strategies really mean and of the organisational changes necessary to implement modularity strategies effectively. Moreover, research and consulting work with automotive companies by this author and others suggests that at least some automotive firms that claim to be doing modular design and development are in fact doing so in name only. In effect, there is evidence that at least some automotive firms have not yet fully grasped the potential strategic uses of modularity or the organisational and process transformations necessary to effectively implement modularity strategies.

This paper undertakes to elaborate the fundamental concepts and principles that must be understood and followed in order to create a real organisational competence in defining and implementing modular strategies in the design, development, production, and after-service processes of any industry, including the automotive industry. This elaboration of the essential concepts and principles on which the effective implementation of modularity strategies depends is intended to establish a benchmark against which managers in the automotive industry (and other industries as well) can evaluate their own organisation's efforts to use modularity. The discussion below also illustrates the principles for effective implementation and use of modularity with examples of both effective and ineffective uses of modularity in the automotive and other industries.

To assure that the practical challenges managers face in implementing modularity strategies are made clear, the discussion in this paper departs from the usual norms of academic research papers to draw extensively on this author's nearly 25-year of research and consulting in defining and implementing modularity strategies in a broad spectrum of industries, including the automotive industry, as well as on a growing body of both published and previously unpublished modularity research. The author's 'action research' approach to researching modularity with companies is summarised in the Appendix.

To assist managers in gauging their firm's relative modularity competence, this paper also develops a modularity maturity model (MMM) for assessing the degree to which a firm has developed and is applying a 'real modularity competence' in automotive design, development, production, and after-service. The MMM highlights, for example, the central role that advanced implementations of modularity are playing in the strategic management processes of some firms and in their processes for organisational learning and knowledge management.

This paper is organised in the following way. Section 2 provides the basic conceptual explanations needed to understand clearly what modularity is and the basic ways in which modularity can be used strategically. Section 2 also describes the interrelated strategic advantages that can be by created by implementing coordinated modularity strategies in design, development, production, and after-service processes. Section 3 elaborates the essential principles on which the effective implementation of modular strategies depends in any industry. Section 4 identifies some of the most common failings of firms in adopting and implementing modularity strategies, and provides some examples of both effective and ineffective implementations of modularity in the automotive industry. Section 5 provides the MMM that managers can use to assess the degree to which a firm has in fact developed a real modularity competence capable of producing significant strategic benefits. Section 6 offers concluding comments on the leadership role that managers must fulfil in order to achieve the significant transformation an organisation will need to undergo in order to effectively implement and use modularity strategies.

2 Architectures, modular architectures, and modular strategies

Many managers and engineers in a variety of industries have had some exposure to some kind of modular product designs and thus believe that they know what modularity is. However, in spite of the success of a few firms in implementing modularity strategies, the limited success that other firms have had in trying to use modularity strategically suggests that, on the contrary, relatively few managers and engineers fully understand what creating modular product designs and pursuing modularity strategies actually entails. And even fewer firms clearly understand how modular design and development processes have to be structured and managed in order to obtain the full strategic benefits available from modular product strategies. The current inability of some firms in the automotive industry to obtain significant strategic benefits from modularity reflects the old management adage, "You can't manage something well if you don't understand it!"

This section provides the conceptual definitions of *architectures, modular architectures*, and *modular strategies* that are now firmly established in management theory and research (Sanchez and Mahoney, 1996, 2013; Baldwin and Clark 2000). Developing a clear understanding of these concepts throughout an organisation is an essential first step in launching any management initiative to use modularity strategically. Since modular strategies depend on creating specific kinds of modular architectures, and since modular architectures are a special kind of architecture, we begin our discussion with the foundational concept of *architecture*. This section also describes the interrelated strategic advantages that can be created by implementing *coordinated modularity strategies* for design, development, production, and after-service processes.

2.1 Architectures

An *architecture* is a way of technically describing or defining the design of any system – whether the system design is for a product, a process, an organisation, or any other entity that is intended to perform one or more functions (Sanchez and Mahoney, 1996, 2013).

An architecture is a two-part concept. First, an architecture defines the way in which the overall functions that a design is intended to perform have been decomposed into specific *functional components* – i.e., the functional 'building blocks' of the design (Sanchez and Collins, 2001; Tu et al., 2004). Second, an architecture also defines the *interfaces* between the functional components that determine how the components in a system design will connect or otherwise interact when the components function together as a system (Sanchez, 1995a, 1995b; Sanchez and Mahoney, 1996). Table 1 shows the six basic types of component interfaces that must be defined in a system design for an assembled product.

Table 1 Types of Interfaces to be described and defined in an architecture

Type of interface	*What the interface specification defines*
Attachment interface	Defines how one component will physically attach to another component
Spatial interface	Defines the physical space a component will occupy in a system design
Transfer interfaces	Defines the input(s) that a component will transform into some kind of output(s)
Control and communication interface	Defines how one component will communicate with and/or control another component
User interfaces	a Defines the intended ways in which a user will interact directly with the components in a system design b Defines how a component will interact with the user's 'macro-system' context
Environmental interfaces	a Defines how a component is expected to interact with the ambient environment of the system design b Defines how the functioning of each component may affect the functioning of other components in the system design

Source: Sanchez (1999)

Creating a system design usually requires working through two stages or levels of architectural specification (Sanchez and Mahoney, 2013; Sanchez, forthcoming). The first stage is concerned with *architectural description*, and the second stage with *architectural definition*.

Describing an architecture requires identifying:

1 the *type of function* each component in a design will perform

2 the *kinds of interfaces* through which the functional components will interact with each other and/or with their surrounding environment.

An architectural description is usually developed during the first conceptualisation of a system design – the stage during which a 'high-level' system design (essentially, 'boxes and arrows') sketches out the main functional components and their primary interactions.

Defining an architecture requires:

1 *specifying the functional and behavioural properties* of each component to a degree sufficient to determine the exact nature of the interactions that will take place between each component and all other components and between each component and its surrounding environment

2 *specifying the exact component interfaces* that will enable the functional components to function together as a system in a defined context and/or across some identified range of conditions.

In effect, an architecture is only fully defined once the specific component types and specific interfaces that will connect the components in a system design have been fully specified.

2.2 Modular architectures

Architectures may be modular or non-modular. A *modular architecture* is one in which the component interfaces have been specified so that an intended range of differentiating component variations can be introduced into the system design without having to make compensating changes either in the designs of other functional components or in any interface specifications. In effect, a modular architecture is one in which some range of functional component variations – whether physical product components or process activity components – can straightforwardly 'plug and play' in a system design (Sanchez and Mahoney, 1996; Sanderson and Uzumeri, 1997; Sanchez, 2004a, 2004b).

A *non-modular architecture* is a system design in which the introduction of a new component variation would require redesigning the architecture to some extent – i.e., making changes in the designs of some other components used in the architecture, and/or creating new interface specifications to manage the interactions between a new component variation and other components. Non-modular system designs may sometimes be created to serve a single intended purpose under well-defined and stable environmental conditions, but they are limited in their strategic usefulness because they cannot be adapted to new purposes or new conditions without making significant changes to their system designs (Sanchez, 1995b; Sanchez and Mahoney, 2013).

In basic respects, creating any kind of system design is an exercise in *optimisation* – a process in which designers have one of two tasks:

1 either maximise some performance attribute(s) subject to cost or other resource constraints

2 minimise cost or some other resource considerations subject to some performance constraint(s).

A fundamentally important design difference between modular and non-modular architectures is that non-modular architectures are the outcome of a *static optimisation* process intended to produce a design that will be effective in serving a single purpose under constant conditions. By contrast, modular architectures are system designs that are the outcome of a *dynamic optimisation* process in which specific forms of flexibility to adapt to some range of changing purposes, demands, or conditions have been 'designed into' the architecture (Sanchez, 1995b, 2004a, 2004b, forthcoming).

Two types of modularity may be used in creating modular architectures (Sanchez, 2008). *Technical modularity* exists in an architecture when at least some interfaces between two or more components allow the direct introduction of some component variations into the architecture without requiring design changes in the architecture (Ulrich, 1995). Technical modularity is often used informally in 'back office' engineering activities to simplify or 'rationalise' designs, most commonly through re-use of standard component designs and/or re-use of existing interface specifications – e.g., adopting a standard wheel bolt pattern for attaching wheel rims to hubs (Sanchez, forthcoming; Sanchez and Mahoney, 2013).

By contrast, *strategic modularity* is created through a strategically motivated design process in which designers consider the various ways in which the overall functions of a design could be decomposed technically to create specific forms of *strategic flexibility* to introduce a range of component variations that enable configuration of a range of product variations – a process that Sanchez (1995b, 2000a, 2008) refers to as the *strategic partitioning* of an architecture (discussed further in Section 3.2). The basic intent of strategic partitioning is two-fold:

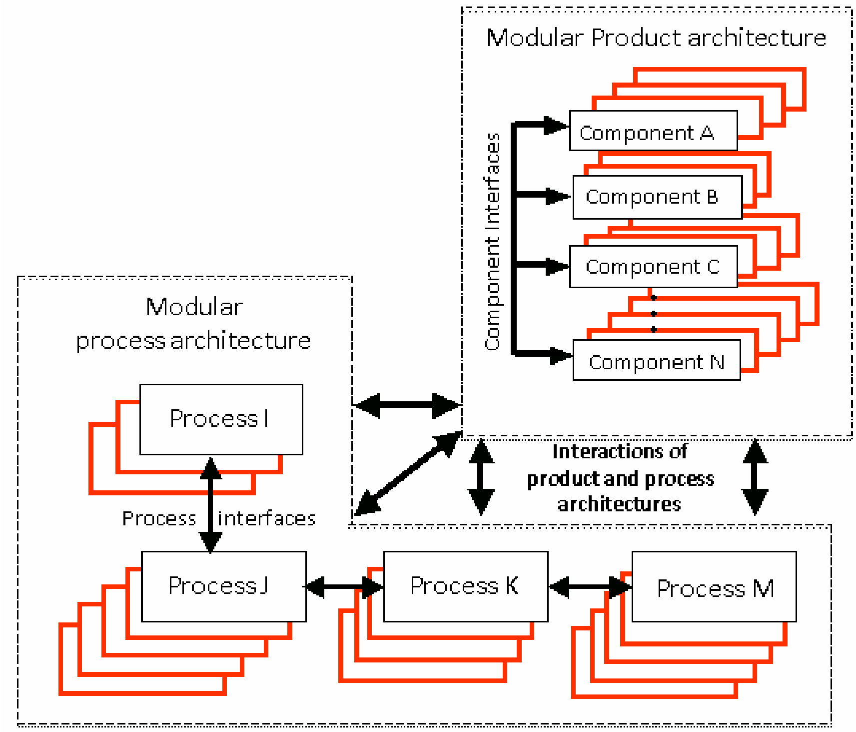
1 to *technically isolate components* that do not need to change during the intended lifetime of the design from those that it would be desirable to be able to change

2 to *achieve a 'one-to-one mapping'* of each strategically important function to be delivered by an architecture into a single functional component (or a single subsystem in more complex architectures like automobiles).

Effective strategic partitioning of a modular architecture enables a range of strategically desirable product design variations to be configured through direct introduction of a range of component (or subsystem) variations into the architecture.

When the designs of a product architecture and its supporting process architecture (e.g., a flexible production process) are strategically coordinated and partitioned so that the configurability of both product and process architectures can be used to support a well-defined strategic objective – such as providing a defined range of product variations and/or configuring higher performing product variations by introducing higher performing components – the combination of the two architectures constitutes a *modular platform* for accomplishing an organisation's strategic objectives (Sanchez, 2004a). Figure 1 illustrates a modular platform consisting of coordinated modular product and process architectures.

Figure 1 A modular platform consisting of coordinated modular product and process architectures (see online version for colours)



2.3 *Modular strategies*

When a firm is competent to create modular architectures that allow the ready substitution of component variations to create new product or process variations, and when the firm is capable of following a disciplined modular development process (discussed further in Section 4), it becomes possible for the firm to pursue new kinds of product strategies and organisation strategies (Sanchez, 1995a, 1995b, 1999, 2004a, 2006, 2008, 2012; Worren et al., 2002). We next summarise the main features of modular product and organisation strategies, and then suggest how modularity strategies for design, development, production, and after-service should be coordinated to achieve the greatest overall strategic benefit.

2.3.1 *Modular product strategies*

Effective creation and use of *strategically modular architectures* may enable an organisation to achieve one or more of four strategic benefits:

1 The ready configurability of new product variations within a modular architecture substantially improves an organisation's ability to *offer greater product variety*. Modular architectures enable the creation of families of products in one development effort, not just single product designs.

2 The ability to introduce technologically improved components into a modular architecture enables *more rapid upgrading of product performance*. Modular architectures make it possible to configure higher performing product variations without undergoing product redesigns.

3 Effective strategic partitioning to enable greater use of common components across product models and/or greater re-use of components across product generations can radically *reduce costs for design, development, production, and servicing of products*. Research from a number of industries has established, for example, that disciplined design for re-use of components can reduce overall development costs by 50 to 80% (Sanchez and Collins, 2000; Sanchez, 2004a, forthcoming).

4 Disciplined adherence to a modular product development process can significantly *improve speed to market for new products.* Research has found that some firms have become four times faster in bringing new products to market through disciplined use of a modular architectural development process (Sanchez, 2004a, forthcoming).

A strategically effective modular architecture may be able to provide significant benefits on all four dimensions named above, but inevitably some trade-offs among these potential benefits will need to be made in creating a specific modular architecture. The development of a strategically effective modular architecture therefore requires that managers clearly define the strategic priorities for a modular architecture. In effect, managers have to clearly define whether design trade-offs that have to be made in the design of the architecture shall be made in favour of enabling greater product variety, faster performance upgrading, greater speed to market, or reducing costs – and in what order of priority (Sanchez, 2004a, 2006).

If a firm develops the competence to create strategically modular product and process architectures, the strategic benefits that it can then design into its modular product architectures may enable the firm to pursue new kinds of product strategies (Sanchez, 1995b, 1999) that would not be possible through use of non-modular architectures. Thus, when one or more firms in an industry begin to use modular product architectures strategically to create more product variety more quickly and at lower costs than competitors, new patterns of product competition are likely to emerge in which the creation of strategically modular architectures becomes a new *dominant logic* and an essential firm competence (Prahalad and Bettis, 1986; Sanchez and Collins, 2001; Sanchez, 1995b, 1999, 2004a; Schilling and Steensma, 2001).

2.3.2 Modular organisation strategies

Sanchez and Mahoney (1996, p.64) proposed a fundamentally important relationship between the product architectures an organisation creates and the organisation architectures it is likely to adopt:

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

In effect, Sanchez and Mahoney (1996) suggest that the product architecture an organisation uses will significantly influence – and thus will *tend to be reflected* in – the kind of organisation architecture it will adopt to develop, produce, and support the products it will derive from its product architecture.[1] For example, the way the component structure in a product architecture has been strategically partitioned into components is very likely to be reflected in the way the overall product development task has been partitioned into specific component development tasks.

Sanchez and Mahoney (1996) went on to point out that standardising the interfaces in modular product architectures can provide *embedded coordination* of loosely-coupled development processes (and production processes as well) and may therefore make possible modular organisation designs based on 'self-managing' component development processes. If a firm follows a modular architecture development process in which it first defines and standardises (i.e., freezes) the interfaces between the functional components in a modular architecture, and then constrains the development of all components to conform to the standardised interface specifications for each component in the modular architecture, then the tasks of developing individual components become 'loosely coupled' and can be undertaken s*imultaneously* by distributed component development teams (Sanchez, 2000a, 2001a, 2001b, 2002a, 2008; Sanchez and Collins, 2001; Sanchez and Mahoney, 1996; Stephan et al., 2008).

Strict adherence by component developers to the standardised interfaces in a modular architecture enables the development activities performed by different functional component development teams within or external to a firm to 'plug and play' in a *concurrent modular component development process*. The overall development process will then not require intensive communication flows or significant managerial intervention to achieve coordination of component development processes. In effect, following a modular development process for developing a modular product architecture enables use of a *modular organisation design* in which distributed development teams can work autonomously in developing components for new architectures (Sanchez, 2000a, 2004a; Sanchez and Collins, 2001; Stephan et al., 2008).

Adopting a modular development process, however, requires a significant transformation in the organisation of development activities in firms that are currently using conventional (non-modular) development methods. Not all organisations are willing or able to undertake the significant organisational changes required to implement modular development processes, and relatively few are likely to have the management vision and organisational discipline needed to adhere to the principles of the modular development process, as discussed further in Section 4. Firms that do succeed in implementing a real modular development process, however, may thereby be able to make significant use of outsourcing and partnering relationships to develop, produce, and service its products and their components.

2.4 Coordinating modularity strategies for design, development, production, and after-service

In industries with significant levels of vertical integration, like the automotive industry, in which at least some firms are largely responsible for the design, development, production, and servicing of their own products, a number of interrelated strategic advantages can be achieved by coordinating a firm's modularity strategies for the design, development, production, and after-service of products. Achieving these advantages, however, requires taking a 'system-wide view' of the full value chain of a firm's activities from design to after-service, and then setting priorities for the strategic benefits that a firm wants to obtain through use of modularity in the designs of its various value chain activities (Sanchez, forthcoming).

Effective coordination of modularity strategies from design to after-service is either achieved or lost in the way a firm decides to strategically partition its product architecture – the first step in a modular design process. Deciding the way that the component structure of a modular architecture will be partitioned requires consideration not just of the range of component variations and resulting product variations a firm would like to be able to configure from the architecture in the future, but also which organisations can and will develop the various types of components needed, which organisations will produce the components (insourcing *versus* outsourcing), how components will be shipped, how and where a product will be assembled, how a product will be serviced and repaired, and how a product will be recycled or otherwise retired. The objective in strategic partitioning is therefore to choose the component structure for an architecture that enables the most strategically advantageous combination of product configurability, product upgradability, time to market, and costs of production, service, repairs, and recycling or recovery.

In the automotive industry today, it is evident that different firms are pursuing different priorities in the way they strategically partition their vehicle architectures. Volkswagen's platform strategy, for example, uses a strategic partitioning of its vehicle architectures that gives priority to achieving significant economies of scale and resulting product cost reductions through extensive use of common components in numerous models leveraged from a single vehicle architecture or 'platform' for several of its vehicle brands, while also enabling low-cost proliferation of new product models on existing platforms (Sanchez, forthcoming).

North American car producers, on the other hand, have tended to strategically partition their vehicle architectures with a priority emphasis on reducing assembly time and costs. Thus, North American vehicle architectures are increasingly being strategically partitioned into relatively fewer and larger subsystems of components (often called 'modules') that are pre-assembled and supplied directly to assembly lines by first-tier suppliers.[2] In addition, in an effort to reduce the labour costs of after-service maintenance and repairs in North America, Ford, General Motors, and Chrysler are increasingly partitioning their vehicle architectures so that entire functional modules can be removed and replaced quickly, rather than having expensive mechanics in North America work on disassembling modules to repair or replace individual parts.

As future vehicles begin to incorporate new kinds of electronic components and even new kinds of power trains and energy sources, as the need to differentiate vehicles in the marketplace and reduce weight to improve fuel efficiency leads automotive firms to try new kinds of materials for car bodies and interior finishes, and as firms seek new channels for distributing and supporting their products, automotive firms are likely to face significant incentives and necessities to increase their outsourcing of components and of whole sub-systems of components (Stephan et al., 2008). Thus, although overall product development still tends to be managed directly by most automotive firms, the need to integrate new kinds of technologies and components into future vehicle architectures suggests that automotive firms will have to develop new competences in organising modular product development processes to effectively coordinate the distributed and concurrent activities of a growing array of suppliers of development services, assembly, and after-service.

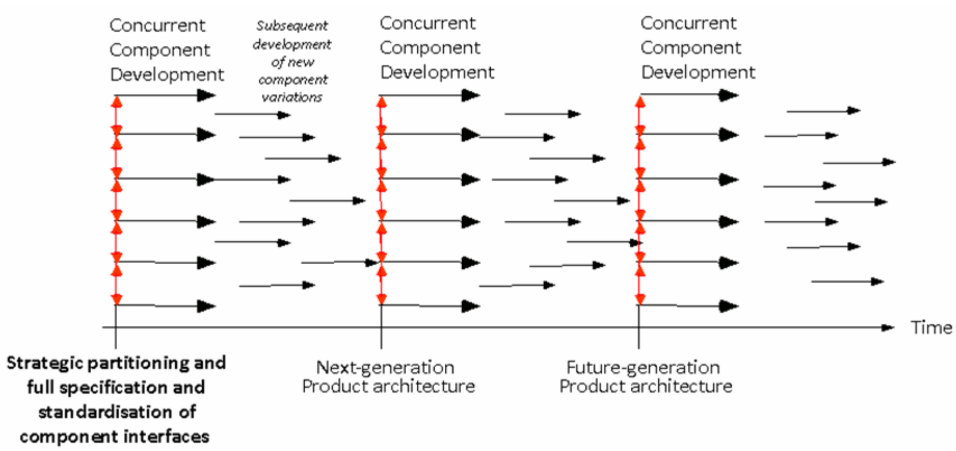
Mercedes' experience in cooperatively developing and producing the Smart car with a dozen or so suppliers in the 1990s provided some important lessons in how to strategically partition and specify interfaces in the Smart's modular architecture to achieve effective coordination of the development, production, and service activities of its various Smart car partners (Stephan et al., 2008). Other automotive producers are likely to have to follow suit in learning how to use the strategic partitioning and interface specifications of their vehicle architectures to enable the participation of a growing variety of suppliers in their development, production, and after-service processes. As a result, automotive firms have to think seriously about how their ability to work with expanded networks of suppliers in all stages of their value chains depends on adopting new priorities – and new competences – in the way they strategically partition their vehicle architectures.

3 The modular architecture development process

Obtaining the full strategic benefits of modular architectures require that firms not only understand clearly what a modular architecture is, but also that they understand and follow the principles of a true modular development process. Although many engineers and managers have some degree of familiarity with modular products, very few actually understand the essential features of a modular architecture development process (Sanchez, 2000a, 2008, forthcoming). As Section 4 will suggest, failure to implement and stick to the essential principles of a modular development process is an all-too-common reason why firms fail to achieve success in developing modular architectures.

This section outlines the fundamental principles of a modular architectural development process that must be understood and followed in order to achieve the strategic benefits of modular architectures, including increased speed to market that can result when a firm can implement simultaneous, distributed component development processes. Figure 2 illustrates the essential features of a modular development process that are discussed below.

Figure 2 'Fast-cycle' modular development process (see online version for colours)



Source: Adapted from Sanchez and Mahoney (1996)

3.1 Freezing product specifications and technology choices

Firms following conventional product development methods often experience disruptions of their development process when the performance specifications for a new product and/or the technologies that will be used in its functional components are allowed to change during a development project. Non-modular product designs typically have many 'tightly coupled' component interfaces – such that a change in the design of one component will require changes in the designs of other components that it interacts with. As a result, making design changes in non-modular architectures to accommodate changes in product specifications or in technology choices for various functional components typically precipitates a chain reaction of design changes in many components, then further design changes in the components that those components interact with, and so on. Research has shown that as much as 50 to 80% of design time in conventional (non-modular) development processes is spent re-designing components because of changes in product or component specifications and the resulting chain reaction of further component design changes (Sanchez, 2004b; Sanchez and Collins, 2001).

Although changes in product specifications and technology choices after development has started are often motivated by managers' desire to assure that the products a firm has under development can match the features and performance levels of the latest products offered by competitors, this well-intended management intent usually results in the opposite effect. Interrupting a development process to include the latest 'bells and whistles' offered by competitors usually significantly slows down the development process – often causing a re-start of the development process – and invariably extends substantially the time to market for a firm's products currently under development.

The modular development process, by contrast, uses a 'fast cycle' development strategy for making sure that a firm's new products are competitive (see Figure 2). Instead of allowing product specifications or technology choices to change during development, a modular process requires that product specifications and technology choices be frozen at the beginning of a development process. Then, using the speed of simultaneous component development (discussed below) that freezing interface specifications enables, a modular development process can often be completed in one-fifth to one-half the time required to complete a conventional development process (Sanchez and Collins, 2001). Thus, over time, a firm doing modular development may be able to 'fast cycle' through development of successive generations of new product architectures and thereby introduce new generations of products at a faster rate than competitors – especially competitors who allow frequent changes to product specifications and other interruptions in their conventional development processes (Sanchez, 2004b).

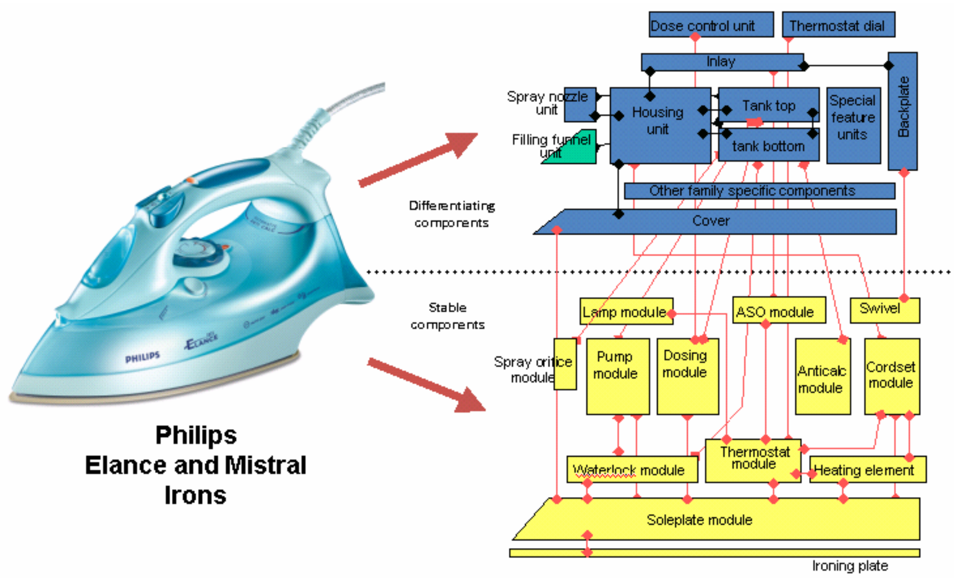
3.2 Strategic partitioning and standardising interfaces

In a conventional development process, both designs of components and the interfaces between components are typically allowed to evolve as development of a new product design progresses. The overall development process is typically organised around and focused on creating new component designs, and the interfaces between components are usually managed in an *ad hoc*, 'as needed' manner (i.e., whenever problems of component incompatibilities arise) or are simply left to the end of the development process to resolve.

In a modular development process, however, the *strategic partitioning* of the architecture and then *fully specifying and standardising the interfaces* between components receive first-priority attention. As suggested in Figure 2, the first step in a modular development process is deciding the most strategically advantageous way of partitioning of an architecture into functional components. In essence, the basic objective of strategic partitioning is to 'contain the variety and change' that will be leveraged from a product architecture in a relatively few components – i.e., to divide the architecture into components that are intended to change and components that are intended to remain stable during the expected lifetime of the product architecture.

The components that are intended to remain the same in effect become the common components used across all or many product variations leveraged from an architecture. Among components that are expected to change during the lifetime of the architecture, however, the second objective of strategic partitioning is to achieve a 'one-to-one mapping' of specific functions and features that will be sources of product differentiation into individual components that can then be varied to configure product variations. Figure 3 illustrates the strategic partitioning of a relatively simple modular product architecture – a Philips iron – but the concept of strategic partitioning remains the same even in more complex product architectures like automobiles.

Figure 3 Example of strategic partitioning of a modular architecture into variable differentiating components and stable common components (see online version for colours)



The interfaces between all components must then be specified to support the ready substitution of an intended range of differentiating component variations into the product architecture (i.e., without having to redesign any other components or re-specify interfaces). The resulting ability to 'plug and play' component variations that are sources of product differentiation perceived by customers then enable a modular product architecture to be used strategically to leverage product variations to meet diverse and evolving market preferences.

Furthermore, once component interfaces are fully specified (not just described) in a modular development process, they must then be standardised – i.e., frozen – so that they will not change during the development process or during the commercial lifetime of the architecture. Freezing interface specifications creates a technically stable architecture of loosely-coupled components, thereby enabling component development tasks to become much less complex and much more predictable technically.

But perhaps the greatest benefit of freezing interface specifications in a modular development process is that standardising interface specifications creates an *information structure* that enables embedded coordination of largely autonomous, concurrent component development processes by internal or external component development teams (Sanchez and Mahoney, 1996). As long as each component development group conforms to the standardised interface specifications for its component, each development group should develop a component that can 'plug and play' in the new modular architecture. Thus, fully specifying and then freezing component interfaces *as a first step* in a modular development process makes possible the concurrent development of components that enables modular development processes to be completed in a faction of the time typically required by conventional development processes.[3]

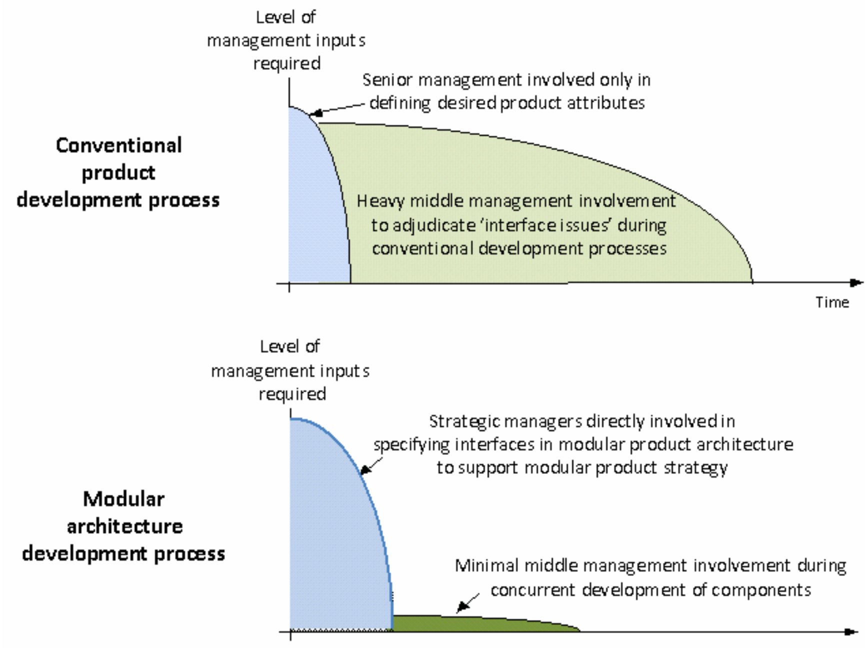
3.3 Strategic managers' involvement in specifying interfaces

In conventional development processes, interfaces between components are generally not recognised by managers as a significant strategic issue, and as a result specifying interfaces is regarded as an essentially technical task.

In a modular development process, however, interface specifications are understood by both management and technical staff to be a highly strategic issue – for the simple reason that the interface specifications in an architecture will fundamentally determine the extent to which component variations can be introduced into an architecture to configure product variations within the architecture. Since modular architectures are commonly intended to be platforms for leveraging product variations and upgrades over some strategic time period, substantial senior management participation is required to define the strategic goals for the product architecture, and then to make sure that the interface specifications defined for an architecture will support the configuring of a strategically desired range of product variations and upgrades.

The strategic nature of interface specifications in a modular architecture and the resulting need to involve strategic managers in deciding interface specifications suggests that modular development processes will have a profile of management inputs and involvement that is quite different from the typical profile of management involvement in conventional development processes. As suggested in the top diagram in Figure 4, strategic managers' involvement in a conventional development process is likely to be limited to an initial discussion of market segments and alternative product performance and cost targets, while the main form of management input is likely to be from mid-level managers (who often have technical rather than strategic backgrounds and responsibilities) who have to try to resolve the many 'interface issues' that typically arise throughout a conventional development process.[4]

Figure 4 Management inputs required in conventional vs. modular development processes (see online version for colours)



By contrast, in a modular development process, strategic managers need to have significant involvement in the earliest stage of a development project to define the strategic goals for leveraging new product variations during the lifetime of a new architecture. Once interfaces that are capable of supporting those goals are specified and frozen, however, there is little need for further management intervention in the development process, since the standardised interface can provide *embedded coordination* of component development processes (Sanchez, forthcoming; Sanchez and Mahoney, 1996), as suggested in the lower diagram in Figure 4.

3.4 Implementing and maintaining a disciplined modular development process

Perhaps the most critical aspect of a modular development process is the need for absolute discipline in following all three of the foregoing principles:

1. strategic partitioning and specifying interfaces are first steps in the development process
2. interfaces are specified strategically, not just technically
3. interface specifications are standardised (frozen) to provide a coordinated, stable technical environment for concurrent, loosely-coupled component development processes.

Frankly, some people who have worked in conventional development processes do not like the new challenge of analysing and specifying interfaces before beginning component development – a process that tends to bring to light what developers do and do not know about component behaviours and how various components will interact in an architecture. Also, people who are used to the lax treatment of interfaces in conventional development processes and thus to freely making ad hoc interface changes may not like the new level of discipline required to freeze and stick with standardised interfaces in developing components.

Implementing a disciplined modular development process requires creating 'new rules and new roles' that have to be realised through a new *architectural management function and process* (Sanchez, 2000a, forthcoming). Since conventional development processes tend to be focused on component development and thus are typically organised and managed by individual component development groups, installing an overarching architectural management function – one of whose primary responsibilities is to assure that component development groups conform to standardised component interfaces – may meet with significant opposition from a firm's current development staff. Senior managers must then have the necessary understanding, commitment, and leadership to motivate their development staff to adhere to the principles of a modular development process. Unfortunately, in many organisations, the necessary understanding, commitment, and leadership by senior management are simply lacking.

3.5 Capturing organisational learning in improved interface specifications

Two forms of technical learning commonly occur during new product development: Learning how to design individual components to perform more predictably (component-level learning), and learning how to specify the interfaces between components so that an overall system design performs more predictably (architectural learning). Since components are also systems whose individual architectures can be made more reliable by improving the interfaces between the parts that make up a component, learning how better to specify interfaces between different kinds of functional components in an architecture – whether the architecture is for a complete product or for a component within a product – is a key form of technical learning to be captured during a development process. Architectural learning is especially important in modular development processes, because it is an organisation's architectural knowledge that enables it to specify reliable interfaces as the first step in a development process (Sanchez, 2000a, 2000b, 2001a, 2002b, forthcoming; Sanchez and Mahoney, 1996, 2013).

At the same time, an organisation's interface specifications can serve as a key repository for capturing and archiving the architectural knowledge a firm develops during development processes and from feedback on product performance after sales. The capture and archiving of key architectural knowledge in a firm's interface specifications may occur in the following way. Suppose that developers have used their current architectural knowledge to specify interfaces for a given architecture, but testing of the product discovers an interface problem – perhaps a control and communication interface problem of two components not correctly receiving or responding to the signals they exchange, or maybe an environmental interface problem of one component generating heat (or vibration, electromagnetic field, etc.) that affects the functioning of another component. When developers analyse and eventually learn how to manage such problems, the knowledge that developers have acquired through their problem solving should be captured organisationally by revising the firm's previous interface specifications to prevent undesirable interactions between those types of components, or by adding new kinds of interface specifications (e.g., a heat, vibration, or EMF control interface) to govern any newly understood interactions between components.

Thus, senior managers should not just understand that interface specifications need to be defined strategically to support an organisation's intended strategic use(s) of an architecture. Managers also need to understand that the interface specifications that a firm develops and carries forward through its development processes should also be recognised and managed as primary repositories for the architectural knowledge created in an organisation's development and debugging processes.

4 Common failings of firms to develop a modularity competence

This section summarises some of the most common failings of firms to understand and implement modularity strategies effectively. The kinds of failures mentioned below are the main reasons why some firms – including those in the automotive industry – fail to develop a real modularity competence. Conversely, firms that have developed significant modularity competence have invariably recognised these potential sources of failure and have taken steps to assure that such failures do not happen in their modular development processes. To illustrate both the nature of these failures and the steps some firms have taken to prevent them, the discussion below provides some examples of both good and poor modularity implementation in the automotive industry.

4.1 Failure to understand modularity and modularity strategies adequately

As simple and unlikely as it may seem, one of the main reasons firms fail to develop a modularity competence is that they have not made an adequate effort to understand what *strategic modularity* and *modularity strategies* really mean. Perhaps because there is a general reluctance in business to spend time on something so abstract as the meanings of words, and perhaps because engineers who have had some exposure to technical modularity do not want to appear wanting in modularity expertise, a surprising number of otherwise sophisticated firms have launched programmes to use modularity strategically – only to fail because there was no clear and consistent organisational understanding of what modularity is and how it can be used strategically.

Philips' Oral Health Care business unit provides an exception to this pattern of failure (Sanchez, 2004a). In 2000, Philips decided to reorganise the struggling powered toothbrush business in its Oral Health Care business unit, and to do so by creating a modular platform of coordinated modular product and process architectures to support new modular strategies to be pursued by the business unit. Senior managers in the Oral Health Care headquarters in Klagenfurt, Austria, wisely decided that they would first invest some precious time and resources in understanding what modularity strategies are all about. Even though Philips' business unit was under severe pressure to improve its financial performance quickly (or face possible closure), managers and engineers together devoted three months to understanding every possible aspect of modularity that they could. They read books and papers on modularity (including papers by this author in academic management journals). They held seminars and workshops with researchers working on modularity strategies (including this author), and they studied the designs and development processes used by firms successfully pursuing modular strategies in a number of industries.

In contrast to many firms that have simply 'jumped into the river before they learned how to swim,' Philips' Oral Health Care unit started its implementation of modular development processes with a clear, common understanding of how strategic partitioning makes strategic modularity different from technical modularity, why interfaces have to be fully specified as a first step in the development process, why interfaces cannot be changed during development processes, how technical learning should be captured in interface specifications, etc. The result was that Philips Oral Health Care business unit was subsequently able to fully and successfully implement a real modular development process on first try. The firm's conversion to modular development processes and modular strategies produced some impressive (but not at all extraordinary) results, achieving a 52% reduction in unit costs, a reduction of lead times from 5 weeks to 5 days, and an improvement to 99+% in the firm's 'line-item performance' in shipping product to customers on time and in the quantity promised. Within four years, this profoundly reorganised and reinvigorated business unit became the clear leader (by sales) in the global market for powered toothbrushes, and it continues to hold a commanding lead today (Sanchez, 2004a).

By contrast, this author knows a European automotive firm that claims to be doing modular design, but that has achieved little or no benefit from 'modularity' – with some of its managers even going so far as to claim that modularity cannot work in the automotive industry because automobiles are 'too complex' for modularity. Although the firm has invested a great deal of time in doing what its managers and engineers call 'modular' development, it has thus far expended a great deal of effort without achieving any significant benefits. In this firm, however, both managers and engineers are rather vague in their understanding of modularity and in fact have a lot of different ideas about what modularity means. Although engineers and managers use the word 'modular' frequently in referring to their development process, in fact there is really nothing at all modular about their development process.

In this firm, interfaces are simply described during the development process and are not fully defined until the last step in the development process – and may even be modified after vehicles have gone into production. Interfaces therefore change frequently during the firm's development process. Moreover, interfaces are defined without strategic managers' inputs to clarify the full range of product variations which the architecture is intended to serve; interfaces therefore tend to be defined narrowly to address purely technical concerns in development, and then have to be changed frequently after development to address needs for new product variations to be leveraged from the architecture. The firm tries to do concurrent component engineering during development, but because interfaces are not frozen at the beginning of the development process, different component development groups end up developing component designs that are not compatible with other development groups' component designs. In effect, this firm is still following a conventional development process, even though everyone in the firm now wrongly calls it 'modular'.

Unfortunately, this firm is not atypical, and other firms have failed to develop a modularity competence for the simple reason that managers and engineers were unwilling to educate themselves adequately about modularity and modularity strategies. To paraphrase the old adage, "You can't become competent in doing something that you really don't understand".

4.2 Failure to implement a new organisation design for modular development processes

Some of the expertise that managers and engineers have developed in conventional development processes will simply be irrelevant to and even counterproductive in a modular development process. As noted above, conversion of a conventional development process to a modular development process requires adopting some essential 'new rules and new roles' (Sanchez, 2000a, forthcoming). Implementing these new rules and the new roles needed to make sure the new rules are followed invariably involves significant changes in the current distribution of responsibilities and authority among development staff. Implementing such changes implies significant shifts in the power structure and relationships in an organisation, and the people who will lose power or see the value of their current expertise diminished are likely to resist making the change to a modular development process (Salancik and Pfeffer, 1977).

Organisational change is not easy, and many managers will go to great lengths to avoid dealing with the difficult issues involved in changing organisation structures and processes. However, trying to implement a modular development process through an existing conventional development organisation structure, or otherwise failing to re-organise development processes to follow the new rules and new roles of modular development processes, virtually assures that an effort to do modular development will fail.

Unfortunately, another automotive firm provides a compelling example. Like virtually all automotive firms, in the late 1990s and early 2000s this firm was rapidly converting many of its vehicle components and subsystems from mechanical and electromechanical technologies to microprocessor-based digital technologies. However, this conversion process posed a new architectural challenge: Many of the mechanical subsystems that had previously been 'islands of technology' within a vehicle now had to be coordinated with other vehicle subsystems in a new 'electronic vehicle architecture' in order to take advantage of new digital technologies, especially for engine management and vehicle control (e.g., integrated monitoring and control of suspension, braking, and steering). The organisation structure used in the firm's conventional development process, however, reflected the old mechanical technology structure of its prior generations of vehicles, with every mechanical subsystem developed by a long-established development group dedicated to a single subsystem.

As more microprocessors and other forms of digital technology were introduced into the firm's vehicle architectures, the need to create a comprehensive electronic architecture to achieve coordination across all vehicle subsystems became acute, in no small measure because of some well publicised failures of various critical vehicle subsystems to work together properly in the firm's vehicles. In spite of the clear and urgent need to introduce a new electronic architecture management role to assure compatibility of the digital controllers and software in vehicle subsystems, the entrenched power structure of existing development groups in the conventional development process refused to give up their authority. They refused to accept and cooperate with an electronic system architect whose role was to assure the compatibility of the microprocessors and software used in each of the vehicle's various subsystems.

Unfortunately, in spite of vehicle reliability problems that were becoming a major corporate issue, senior corporate management was reluctant to intervene to force a change in the firm's decades-old development processes. As a result, a misalignment persisted between the conventional, subsystem-focused development process the firm continued to use and the new electronic architecture coordination function the firm now needed to assure the reliable functioning of its vehicles. The consequence was catastrophic technical failures of the electronics in a new generation of top models that were loaded with electronic subsystems that simply did not work together reliably. Only a major management shake-up followed by a major re-organisation of the development process enabled the firm to achieve the new architectural coordination it needed to design and develop reliable vehicles.

4.3 Failure to partition architectures strategically

Creating a modular product architecture (supported by an appropriate process architecture) that can serve as a platform for strategic leveraging of product variety, upgrading of products, increasing speed to market, and/or reducing product costs requires careful strategic partitioning of the product architecture – and thus significant inputs by strategic-level managers as to the strategic priorities of the firm. If a modular architecture is partitioned without clear strategic priorities and thus does not enable the firm to obtain specific desired strategic benefits from the architecture, the modular architecture will have largely been created in vain.

Unfortunately, in many if not most organisations, strategic managers are likely to regard architectural design matters as 'an engineering issue' and rarely if ever become involved in discussing the strategic implications of alternative approaches to partitioning architectures. The author's work with numerous companies across a variety of industries suggests that initiatives to 'do modular architectures' are likely to fail to produce any real benefit unless top management recognises the strategic implications of the way an architecture is strategically partitioned and interfaces specified or otherwise fails to provide adequate guidance as to the strategic priorities that will need to be served by the modular architecture.

4.4 Failure to fully specify interfaces

The ability to radically reduce development time through concurrent development of components – as well as to efficiently contract for development services outside the firm – depends fundamentally on the standardisation of *fully specified interfaces* as a first step in a development process.

Because interfaces are allowed to evolve during a conventional development process, many developers have never been challenged to try to work out viable interface specifications *before* component development begins. As a result many developers are somewhat intimidated by the idea of specifying interfaces at the beginning of development, and some even go so far as to claim that it is not technically possible to do so. Although a development group's first effort to fully specify interfaces first may not be completely successful, full and correct specification of interfaces *before* beginning component development must become respected as a fundamental principle in modular development processes. Failure by developers and/or their managers to fully define interface specifications before beginning component development virtually assures that component development cannot be carried out through distributed or concurrent development processes – and thus will not achieve substantial reductions in development time.

4.5 Failure to respect standardised interfaces

Modular development requires fully specifying interfaces at the beginning of a modular development process and then sticking to the specified interfaces throughout component development. This 'new rule' for modular development requires a higher level of discipline in managing interfaces than many organisations following conventional development processes have ever contemplated or managed to achieve. Such organisations are likely to be seriously challenged to assure that component developers adhere to standardised interface specifications during their first efforts to do modular development.

Initial efforts to standardise interfaces in various Philips' business units' conversion to modular development processes in the late 1990s quickly encountered problems when developers continued to change interface specifications that had been 'frozen.' On investigation, Philips' managers discovered that many developers either thought that standardising interfaces as a first step was a kind of goal but not an actual 'new rule' for development, or thought that fully specifying interfaces before developing components was simply not possible technically and so did not really try to do so. To emphasise that standardising interface specifications before beginning component development was a 'non-negotiable' rule for modular development, Philips adopted a policy that was communicated to all developers: "In Philips the standardized interfaces in a new product architecture are *holy*. Once interfaces are standardized in an architecture, not even the Pope can change them – so don't you try!" That management message seemed to get the point across, and early problems in implementing modular development in Philips were largely resolved once developers understood that standardised interfaces *must* be adhered to throughout a modular development process.

4.6 Failure to capture learning by improving interface specifications

In firms with a history of letting interfaces evolve during development of components, architectural knowledge developed in prior development projects usually remains in tacit form in the heads of developers involved in working out prior interface problems. As long as such knowledge is allowed to remain in tacit form, the ability of an organisation to benefit from prior learning will tend to be compromised by a host of organisational factors (Sanchez, 1997, 2005a, 2005b). People with critical tacit knowledge may leave the organisation, may not be assigned to a project where that knowledge is needed most, or may simply forget what they learned. The lack of effective processes for capturing such learning and preserving it in a form that the organisation can access again when needed leads to a common phenomenon in conventional development processes summed up by developer comments like, "We keep encountering the same problems over and over, and we seem to keep reinventing the wheel every time we do another project".

In a modular development process, any architectural learning about how to define and manage the interactions of components in an architecture should be captured in the form of improved interface specifications that then become available to all developers. In the most advanced modular development organisations, such as GE Fanuc Automation

(Sanchez and Collins, 2001), all developers are required to use the established company interface specifications for the various types of components to be used in its architectures, and any problems that arise with those specifications must be solved and the learning captured in the form of improved interface specifications that will avoid such problems in future architectures. Firms that lack such processes for capturing tacit knowledge and converting it to explicit organisational knowledge in the form of improved interface specifications are very likely to end up 'reinventing the wheel' every time they undertake new development projects (Sanchez and Collins, 2001; Sanchez, 2005a, 2005b) – and thereby will fail to achieve a real competence in modular development.

4.7 Failure of management to lead a strategic change process

Implementing a modular architectural process invariably involves significant organisational change, especially in the form of new rules that have to be followed in development and new roles (task allocations and authority distributions) intended to assure that the new rules are followed (Sanchez, 2000a, forthcoming; Sanchez and Heene, 2002). In general, significant organisational change is unlikely to be accomplished without close, committed top management support for such change. Converting an organisation from conventional to modular development and modular strategies is no exception.

The author's research and consulting with numerous firms suggests that the greatest determinant of success or failure of an initiative to implement modularity is the degree of senior management understanding of and support for modularity strategies and for the significant organisational changes needed to implement modularity strategies. When senior managers fail to provide the leadership needed to convert the firm to a modular development process, any efforts of developers and mid-level mangers to develop modular architectures are unlikely to succeed, because the significant interrelated organisational changes needed to implement modular development processes will almost assuredly exceed the authority of mid-level managers to make necessary organisational changes.

The author has witnessed several efforts of mid-level managers to implement modularity without an adequate level of understanding and support from top management. Such initiatives have invariably failed because top management did not understand or support the significant organisational changes needed to implement modular development processes. Firms whose top managers do not understand modularity or who are not willing to lead a significant organisational change process to implement modularity are unlikely to ever put a modular development process in place – and thus are unlikely to ever develop any level of modularity competence.

5 Modularity maturity model (MMM)

This section draws on the author's extensive research and consulting in the automotive and other industries to propose a MMM that is intended to help an organisation assess the extent to which it has developed a real modularity competence. The MMM defines seven levels of maturity in an organisation's understanding and use of modularity. Each maturity level is discussed below and summarised in Table 2.

Table 2 Modularity maturity model

Maturity level	*Management understanding*	*Design and development activities*
7	Modularity as framework for *identifying and developing new strategic competences*	Architectural management function is directly involved in *identifying goals for strategic competence development*
6	Modularity as framework for *strategic integration*	Architectural management function is directly involved in *setting market, technology, and business strategies*
5	Modularity as framework for *knowledge management*	New architectural knowledge created in development is captured in *improved interface specifications*
4	Modularity seen as means to *reduce time to market*	Modular development process based on 'new rules and new roles' enables *concurrent component development*
3	Modularity seen as means to *increase product variety*	*Strategic partitioning* decouples stable from variable components to enable low-cost configuration of product variations
2A and 2B	Modularity seen as means to *reduce product costs*	Early form of modular development process seeks to design (2A) *common components* and (2B) *re-usable components*
1	Modularity seen only as *engineering issue*	Conventional development process uses *technical modularity* to moderately reduce design time and cost
0	Unaware of modularity	Conventional development process makes no systematic use of modularity

5.1 Modularity maturity level zero (MM0)

At this level a firm lacks any modularity competence at all. Managers – especially senior managers who influence a firm's strategies – are unaware of modularity as an important aspect of design and strategy and thus do not understand any of the potential strategic benefits obtainable through modular design.

Accordingly, there is no regular, systematic use of modularity in designing the organisation's products or processes.

5.2 Modularity maturity level one (MM1): technical modularity

In an organisation at modularity level one (MM1), senior managers have some awareness of modularity, but see it as a 'purely engineering issue' to be dealt with by technical staff. As a result, managers have not adopted any goals for the use of modularity in setting their product strategies.

In the organisation's development processes, modularity may be used in a purely technical way to 'rationalise' a firm's various product designs, usually by adopting standard component designs and interface specifications to reduce engineering design time and cost, and to eliminate unnecessary component variety. Standard component designs and interface specifications may either be based on 'off the shelf' industry standard components and interfaces or firm-specific components and interface specifications previously developed within the organisation. Technical staff generally makes these decisions without consulting mangers.

5.3 Modularity maturity level two (MM2-A and MM2-B): common and/or re-usable components

At modularity level two, managers perceive modularity to be a means to reduce the costs of the organisation's products and/or processes through modular design strategies focused on increasing use of common components and/or re-usable components.[5]

As a result, in the organisation's development processes, development staff undertake systematic efforts to reduce product unit cost through use of standard components. These efforts may pursue one of two objectives, which are distinguished here as Modularity Maturity Levels MM2-A and MM2-B. In the case of MM2-A, the firm's development processes routinely create product and process architectures that incorporate *common components* – components that are intentionally designed to be used in common across more than one product or process variation to be configured within a given architecture. Alternatively, a firm may decide to incorporate one or more industry standard components in its product architectures (Sanchez, 2008; Sanchez et al., 2012).

At maturity level MM2-B, development processes routinely undertake to create *re-usable components* – components that are intentionally designed to be used as common components not just in an architecture currently under development, but also in one or more future generation architectures. Designs of components intended to be re-usable may be maintained in a 'design library' of available component designs. Creation of re-usable components involves a longer term and thus more strategic assessment of an organisation's future product strategies and supporting development plans than simply creating components that can work in product variations leveraged from an organisation's current-generation architectures. Thus, development processes that seek to create re-usable components represent a higher level of modularity maturity in an organisation than processes that seek only to expand use of common components in current generation architectures.

5.4 Modularity maturity level three (MM3): configuring product variety

In an organisation at modularity level three, senior managers have realised that the development and production costs of new product variations can be substantially reduced when an architecture has been strategically partitioned into common (and possibly re-usable) components, on the one hand, and components that are likely to change during the lifetime of an architecture, on the other hand. Managers have come to understand that the costs required to develop and produce new product variations are substantially reduced when only a few components have to be changed to configure new product variations, while other components in a current architecture can simply be used in common across product variations. As a result, managers decide to make strategic use of the faster and less costly configurability of modular architectures by adopting market strategies based on offering greater product variety.

Accordingly, development staff routinely undertakes strategic partitioning of an architecture under development to technically isolate components that will be upgraded technologically or produced in variations suitable for different market segments from components that will remain stable and be used in common across product variations leveraged within the architecture. Development of new product variations then focuses on developing technologically upgraded, higher-performing components and/or components that can be used to differentiate product variations for different market segments.

5.5 Modularity maturity level four (MM4): reduced time to market

In an organisation at modularity level four, senior managers have realised that following a true modular development process can greatly reduce the time as well as cost required to create new products, and thus have decided to implement and support a true modular development process (see Section 3) as a means to create a strategic competitive benefit of greater speed to market.

Accordingly, the organisation's development process has adopted and adheres to the 'new rules and new roles' required to implement modular development: interfaces are fully specified and standardised (frozen) before beginning component development, development of components is constrained to conform to the standardised interface specifications for the architecture, and product and process architects monitor the overall development process to ensure that interfaces are adhered to and that new or existing component designs are used in common wherever strategically desirable.

5.6 Modularity maturity level five (MM5): knowledge management and organisational learning

In an organisation at modularity level five (MM5), senior managers understand that following a modular development process can not only greatly reduce development time and costs, but also provide a powerful framework for managing organisational knowledge and for targeting organisational learning.

Accordingly, the organisation's development process is not only disciplined in adhering to the 'new rules and new roles' required to implement modular development, but has also put in place a process for continuous architectural learning. The focus of this learning process is the continuous improvement of the organisation's ability to specify robust, reliable component interfaces, both within an overall product or process architecture and within individual component designs within an architecture. This architectural learning is captured in a continuously refined and improved set of interface specifications for the various kinds of components that are incorporated in the architectures the organisation creates. When a current component interface specification is discovered to be inadequate to assure reliable functioning of an architecture, the organisation engages in root-cause analysis of all product or process failures to determine what new kinds of component interactions need to be recognised and managed through improved or expanded interface specifications – e.g., existing interface specifications for components may need to be more robustly or precisely specified, and previously unrecognised interactions between components (like heat, electromagnetic fields, or vibration) may need to be recognised, analysed, and added to the environmental interface specifications for given types of components (see Table 1).

As the organisation's knowledge of how to control interactions between the components in an architecture (or between the parts in a component architecture) grows, its architectural knowledge can be leveraged widely and quickly through re-use of standard interface specifications developed within the organisation for the various components used in its architectures. In this way, both managers and developers begin to view interface specifications not just as an issue to be dealt with strategically during development, but also as repositories of technical learning that is critical to the organisation's ability to create reliably performing architectures.

5.7 Modularity maturity level six (MM6): integration of marketing, technology, and business strategies

At modularity level six, strategic managers have come to understand that the architectures the organisation creates both enable and constrain a firm's future ability to serve targeted market demands, in effect determining the firm's strategic flexibility to respond to changes in market demands and to changes in the components and technologies it can use to serve those demands. In essence, managers recognise that the product and process architectures the organisation creates provide the platforms it will be able to use in pursuing its business strategies. Accordingly, managers view the processes of defining and creating new architectures as a critical strategic process in which an architectural infrastructure for effective integration of future marketing, technology, and business strategies is either achieved or lost.

At MM6, the definition of next and future generation architectures is regarded as an essential, central part of the strategic management process of the organisation. Technical staff with architectural management responsibilities are therefore regarded as integral participants in the organisation's processes for defining and implementing its strategies, and work directly with strategic-level managers in processes to assure that the organisation's architectures will reflect an effective integration of the organisation's marketing, technology, and business strategies.

5.8 Modularity maturity level seven (MM7): strategic competence development

At modularity level seven, strategic managers recognise that since the architectures the organisation is able to create essentially determine the firm's ability to serve evolving market demands, the organisation's ability to create architectures should be considered a 'core competence' of the organisation (Prahalad and Hamel, 1990). Thus, the process of defining and planning for future architectures is seen as the ideal forum for identifying the new and improved capabilities the organisation will need to develop to compete effectively in the future (Sanchez and Mahoney, 2001).

Architectural managers are therefore seen as essential partners in the organisation's strategic processes for identifying and assessing its future competence requirements (Sanchez, 2000a, 2000b, forthcoming).

6 Conclusions: strategic managers' essential role in building real modularity competence

Sanchez and Heene (2004, pp.2–8) have characterised the role of strategic managers as that of designers of organisations as systems for sustainable value creation and value distribution. They go on to suggest that in performing their role as system designers of organisations, strategic managers "must provide intellectual leadership...for discovering market opportunities and designing value creation and distribution processes" [Sanchez and Heene, (2004), pp.144–145]. In so doing, managers will face 'a unique intellectual challenge' of 'learning to manage their own cognitive processes'. In effect, the strategic managers of an organisation must be the most willing of all to look beyond familiar strategies and ways of managing and to examine and explore new kinds of strategies and new ideas for structuring organisations and their processes.

As suggested by modularity researchers in the 1990s – and confirmed in numerous firm and industry studies since then[6] – modularity does indeed provide a fundamentally new approach not just to designing products, but to pursuing new kinds of strategies and to creating new kinds of organisation architectures and processes capable of accomplishing strategic objectives that are simply not possible to achieve through non-modular product and process designs, conventional development processes, and traditional product strategies. Converting an organisation to modular strategies and processes requires a major strategic change process that can only be achieved if a firm's top managers fully understand and commit to supporting real modularity strategies, processes, and competences.

This author's experience in working with numerous organisations trying to implement modularity strategies suggests that inadequate and even erroneous understanding of modularity and modularity strategies by strategic-level managers, as well as by operational managers and technical staff, is not only very common, but is likely to be the most important factor limiting an organisation's ability to adopt modularity strategies and develop a real modularity competence. Managers – especially senior managers – are likely to see architectures in general and modularity in particular as simply an engineering issue, and thus to fail to recognise the fundamental role that product and process architectures play in enabling an organisation's overall strategies.

As a result, the 'default mode' in organisations is by no means a ready ability to define and implement modularity strategies. On the contrary, the norm in organisations today is still an inability to define and implement modularity strategies – largely because of inadequate and divergent conceptual understandings within firms of the fundamental roles that architectures and modularity can play in enabling firm strategies. In this all too common scenario, however, the greater responsibility for an organisation's inability to undertake real modularity initiatives and to advance to higher levels of maturity in its modularity competence is likely to lie with senior and mid-level managers, whose understanding and support are essential to the ability of an organisation to undergo a strategic change process. Senior managers therefore have an especially critical impact on the ability of an organisation to move beyond conventional development processes and to develop new modularity strategies and competences.

When senior managers do not adequately understand modularity and its potential strategic uses, they will – quite understandably – be reluctant to support the far-reaching strategic changes an organisation must undergo in order to define and implement modularity strategies. Mid-level managers may also be reluctant to give up the decision-making discretion they commonly have in conventional development processes (for example, in resolving interface issues – see endnote 4) in favour of the much more highly defined, structured, and transparent processes for defining and managing architectures needed in modular strategies and development processes. Top management understanding of and commitment to implementing modular strategies then becomes essential to overcoming their own hesitations to undertake strategic change, as well as any mid-level management resistance to adopting modularity strategies.

Unfortunately, the old adage to the effect that "significant organizational change is only possible when there is a real crisis" seems to apply with particular force to an organisation's ability to change to modular strategies and development processes. In this author's experience in working with many companies to implement modularity strategies, the most successful implementations of modularity have been by firms whose ability to compete effectively through conventional development processes was clearly becoming inadequate, who were as a result beginning to perform poorly, and whose managers were finally willing to contemplate radical change in business strategies and development processes in order to survive in their product markets (Sanchez, 2004a, 2004b, forthcoming).

In some exceptional cases known to the author, however, some forward-looking managers have recognised that tremendous competitive advantages can accrue to the first organisations to 'go modular' in their industries, and in the long run to firms that become more competent in defining and implementing modular strategies and processes than their competitors. In these cases, the few managers willing to take the risk of leading their currently successful organisations in adopting new modularity strategies have been able to build and use a continuously improving modularity competence to bring their firms substantial market gains and significant improvements in profitability (Sanchez and Collins, 2001; Sanchez, 2004a).

This author's research therefore suggests that successful adoption and implementation of modularity strategies and the building of real modularity competences to support modularity strategies must start at the top management level of an organisation. Efforts by mid-level or technical managers to implement modularity strategies and processes are extremely unlikely to succeed unless top managers clearly understand modularity strategies and are willing to support the significant organisational changes needed to implement modularity strategies. In the worst cases, efforts by mid-level managers to adopt modularity strategies without top management understanding and support have not only failed, but have created serious organisational conflicts resulting in deep organisational aversion to any efforts to use modularity in any systematic way. In one instance, managers went so far as to ban the use of the term 'modularity' in management discourse because of rancorous feelings resulting from previous failed efforts by mid-level managers and technical staff to implement modularity strategies without top management understanding and support.

This author's involvement in both successful and unsuccessful efforts to implement modularity strategies leads to a clear conclusion: development of a real modularity competence in the automotive industry, as in any other industry, depends most critically on:

1 strategic-level managers' correct understanding of modularity strategies and supporting processes

2 strategic-level managers' willingness to lead their organisations in the substantial strategic change process necessary to convert from conventional to modular development processes and product strategies.

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Notes

1 In the management research literature, this proposition is usually referred to as the *mirroring hypothesis* (Sanchez and Mahoney, 1996, 2013).

2 This strategic objective for modular product architecture has its logical extension in Volkswagen's 'modular consortium' truck and bus factory in Brazil, in which first tier module suppliers directly install their modules on the rolling assembly line, providing virtually all the assembly labour needed to build a vehicle (Marx et al., 1997; Pires, 1998).

3 Various approaches to 'simultaneous development', 'concurrent engineering', etc., have been proposed and tried by various firms. However, any approach to parallel, concurrent development of components that does not first standardise the interfaces between components will inevitably result in 'concurrent chaos', because no set of components can be designed to

work together reliably as a system until all interfaces between components are fully specified and stable (Sanchez, 2000a, 2013).

4 'Interface issues' typically arise when incompatibilities in the interactions between two or more components under development are discovered in conventional development processes (i.e., when interfaces are not fully specified and frozen at the beginning of the development process). Interface issues tend to be of three main types:

a Should there be a change in the interface specifications between two or more components?

b If so, what should the new interfaces be?

c To whom should the additional development costs for developing new interface specifications be charged?

Answering the first two questions requires a strategic perspective on the role the new product architecture will play in the firm's overall strategy, but in conventional development processes these issues are commonly addressed not by strategic managers, but by technical development managers who may lack an adequate strategic perspective to make good decisions about interface specifications. The third issue is likely to be a source of considerable contention if not decided on the basis of a clear set of strategic priorities – which also requires a strategic (rather than operational) management perspective (see Sanchez and Collins, 2001; Sanchez 2013).

5 In this discussion, the term *common components* refers to component designs that are used simultaneously in all or many of the organisation's current generation of product and process architectures. *Re-usable components* are those that are re-used in successive generations of product and process designs – either by strategic intent or as a result of fortuitous circumstances (e.g., a current generation component can be re-used in a next generation architecture without compromising the performance level of next generation products or processes).

6 For an overview of research to date on the impacts of modularity on firm processes and performance, see Sanchez and Mahoney, 2013, footnote 6. For reviews of the development of modularity in management studies, see Campagnolo and Camuffo (2010), Fixson (2007), Jacobs et al. (2007) and Salvador (2007).

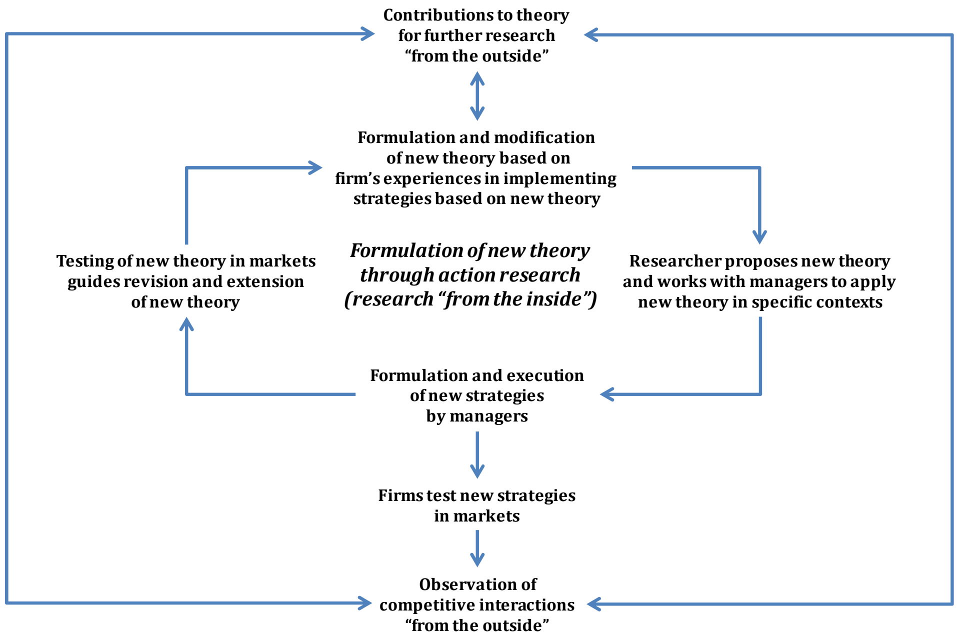
Appendix

Author's 'action research' methodology

Most of the research on which this paper's observations and prescriptions are derived may be described as 'action research' in which the researcher (this author) has actively engaged in a variety of market tests of strategies based on modularity theory with a number of firms willing to adopt and implement modular architectures and modular product strategies.

This mode of research has been suggested by Mahoney and Sanchez (2004) in advocating that management researchers become more involved in pragmatic tests of management theories by engaging with managers willing to learn about, adopt, and test new strategies based on new management theories. This mode of research is illustrated in Figure A1.

Figure A1 Model of author's 'action research' methodology (see online version for colours)



Source: Adapted from Figure 2, Mahoney and Sanchez (2004, p.41)

Using the terminology of Evered and Louis (1981), Mahoney and Sanchez suggest that at least some management researchers should engage in research 'from the inside' of organisations by observing and interacting directly with firms and managers to test new management and strategy theories in practice. Such observations can lead to important refinements and even corrections of management theories that have not been directly exposed to market tests. When new strategies based on new theories are exposed to markets tests, traditional research 'from the outside' that relies solely on external observations of firms' market interactions can also take place. Mahoney and Sanchez (2004) suggest that both modes of research – research from the inside and research from the outside – are needed to develop robust management theories, to understand the limits of those theories as foundations for strategies, and to appreciate more fully the actual challenges that managers will face in implementing strategies based on new theories.

In practice, the 'action research' on which this paper is based was sometimes conducted as 'pure research', and sometimes as part of a paid consulting arrangement. The deciding factor was whether a particular engagement by the author with a firm could lead to a publishable research paper (in which case the engagement was considered 'pure research'), or whether a firm preferred that the results of the engagement remain confidential (in which case the engagement was treated as paid consulting). However, in a number of cases, research that was originally undertaken as paid consulting could later be reported as research when companies eventually gave permission to publish action research outcomes that were initially regarded as too strategically sensitive to publicise.