Discussion Paper Series

AGISSS

Gakushuin University

No. 2020-2

Modularity Design Rules for Architecture Development: Theory, Implementation, and Evidence

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Abstract

In this paper we propose a set of rules for developing modular architectures. We extend the technical concept of "Design Rules" advanced by Baldwin and Clark (2000) and propose a set of *normative* "Modularity Design Rules" derived from subsequent research into the *strategic, managerial, and organizational processes* that must be also undertaken to implement successful modular development projects. We then provide support for the proposed Modularity Design Rules through a case study of the Renault-Nissan Alliance's successful development and use of a modular "Common Module Family" architecture.

Key Words: Design Rules, Architectures, Modularity, Product Development.

INTRODUCTION

Beginning in the 1990s, a major new stream of management research began to investigate how the *architectures* a firm adopts for its product designs may affect the kinds of strategies a firm may pursue in its product markets (Garud and Kumaraswamy 1995; Sanchez 1995, 1999; Sanchez and Mahoney 1996; Robertson and Ulrich, 1998; Shibata, Yano and Kodama, 2005; Shibata, 2009). Research in this stream established rather conclusively that use of *modular architectures* may enable firms to significantly reduce overall development times and costs, increase speed to market, *and* increase product variety (Langlois and Robertson 1992; Sanchez 1995, 1999, 2008; Sanchez and Mahoney 1996; Chesbrough and Kusunoki 2001; Worren, Moore and Cardona 2002; Sanchez and Hang 2017).

A number of firms in a variety of industries have successfully developed modular architectures and achieved significant strategic benefits thereby, but many other firms have failed to develop or use modular architectures successfully. Some researchers who have studied both successful and unsuccessful modularity initiatives in firms have suggested that *new kinds of management processes and organization structures* are required to achieve success in developing modular architectures (Sanchez 2000; Sanchez and Collins 2001).

These new kinds of processes and structures differ fundamentally from practices typically used in conventional new product development (NPD) processes, as well as from practices like "overlapping problem solving" (Clark and Fujimoto 1991) that try to improve the speed of conventional NPD processes (Sanchez 2000, 2008; Sanchez and Collins 2001; Colfer and Baldwin 2010). As a consequence, both technical and strategic managers are likely to face significant challenges in understanding and implementing new management processes and organization structures in converting their firms from conventional NPD processes to modular development processes.

In conventional NPD processes, technical managers are typically focused on developing new kinds of components for next-generation products, while the interfaces that must connect the new components under development are (necessarily) allowed to "evolve" during component development processes. In implementing modular development processes, however, technical managers are likely to be challenged because modular development processes require fully specifying, freezing, and adhering to interface specifications as the first step in modular development processes -- i.e., before beginning development of new components. Fully specifying component interfaces before beginning component development, however, creates an "information structure" (Sanchez and Mahoney 1996) that can enable a firm and its suppliers to undertake *concurrent component development processes* that can significantly reduce overall development times.

For their part, strategic managers are likely to be challenged by the need to *adequately define the strategic objectives* for each new modular product architecture before beginning modular development processes (Sanchez 2000, 2013, 2015). Adequately defining the strategic objectives for a new architecture is essential to determining (i) the most advantageous *strategic partitioning* of the new architecture into functional components and (ii) the most effective *specifications of interfaces* between components -- both of which are needed to create a modular architecture that can provide a strategically intended range of product variations and upgrades derived from the configurability of components within the new modular architecture (Sanchez and Mahoney 1996; Sanchez 2000).

Moreover, as we elaborate below, to create a new modular architecture, technical and strategic managers must also interact through a *specific sequence of information exchanges and decision-making steps.* These information flows and decision-making processes form the core of the new management processes and supporting organization structures that we propose are essential to successful creation of modular architectures.

In their well-known study of the technical structure of the IBM System 360 computer architecture, Baldwin and Clark (2000) concluded that certain essentially *technical* "Design Rules" must be followed in order to create a modular product architecture. At the same time and subsequently, using "real-time" research methods to investigate efforts by firms in a number of industries to implement modular development processes, Sanchez (2000, 2013, 2015) proposed that managing modular development processes requires following certain "new rules and new roles" that differ fundamentally from management practices in conventional NPD.

In this paper, we elaborate a formal set of *Modularity Design Rules* ("MDRs") that identify specific strategic, managerial, and organizational practices that we suggest are essential to achieving success in modular development processes. We also undertake to lend some measure of empirical support to the proposed MDRs by reporting some key findings from a multi-year longitudinal study of the Renault-Nissan Alliance's (RNA) highly successful initiative to create a "Common Module Family" (CMF) modular architecture.[1] We suggest how RNA's success in creating the CMF modular architecture followed largely from (i) RNA management's realization of the need for new kinds of management processes and organization structures, and (ii) RNA's implementation of new management processes and organization structures that closely mirror the MDRs we propose here.

Our discussion is structured in the following way:

In Section 1 we compare the essentially technical concept of Design Rules suggested by Baldwin and Clark (2000) with the managerial and organizational perspectives on modular architecture development processes proposed by Sanchez (2000).

In Section 2 we elaborate our proposed set of 10 Modularity Design Rules and explain both the theoretical basis and practical considerations motivating each rule.

In Section 3 we present an overview of longitudinal study of Renault-Nissan Alliance's development of its first "Common Module Family" modular architecture.

Section 4 summarizes the key findings from our case study that we believe lend support to the Modularity Design Rules we propose here.

Section 5 offers concluding comments.

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[1] We note that the CMF modular architecture development process undertaken jointly by Renault and Nissan precedes by several years the recent disagreements between Renault and Nissan over ownership interests and a possible effort by Renault to take over Nissan.

1. "DESIGN RULES" RECONSIDERED

In the mid-1990s some management researchers began to observe that some firms using modular product designs successfully had adopted new kinds of management processes and organizational forms to support their development of modular product architectures (Garud and Kumaraswamy 1995; Sanchez 1995; Sanchez and Mahoney 1996). In 2000, two key studies offered some early insights into the nature of the development processes that firms could use to create modular architectures.

In 2000 Baldwin and Clark published their well-known book *Design Rules*, based largely on their historical study of the technical structure of the 1960s IBM System 360 computer's modular architecture. Adapting the Quality Function Deployment matrix used in Total Quality Management (Hauser and Clausing 1988), Baldwin and Clark developed a "Design Structure Matrix" ("DSM") for identifying the interactions among components within a product design. Their DSM analysis showed that certain components in the IBM System 360 were intentionally isolated or "decoupled" technically from other components -- thereby enabling the introduction of component variations to configure a range of product variations for meeting different customer requirements for computing. Baldwin and Clark then proposed a set of "Design Rules" for creating technical decoupling among components during the architecture development process.

Concurrently, based on several "real-time" studies of ongoing modular development processes in Philips, General Electric, Chrysler, and other firms, Sanchez (2000) proposed that achieving success in creating modular architectures requires new approaches to organizing and managing development processes. In effect, Sanchez (2000) argued that the technical design rules revealed through DSM analyses in the manner proposed by Baldwin and Clark (2000) can only be implemented successfully when a firm has first adopted a set of "new rules and new roles" for organizing and managing modular development processes.

In the next section, we draw on and extend this broader perspective to elaborate a set of 10 Modularity Design Rules (MDRs) for carrying out the organization and management of modular development processes.

2. MODULARITY DESIGN RULES (MDRs)

We begin our elaboration of new rules for managing modular architecture development processes by making a critical distinction between "technical modularity" and "strategic modularity" in product designs. We then elaborate the 10 MDRs in three categories: (i) rules that apply to strategic, organizational, and managerial processes to be undertaken *before* beginning technical development of the components to be used in an architecture (Section 2.2), (ii) rules that apply most critically *during* the technical development of components (Section 2.3), and (iii) rules that apply *after* the technical development of components and during the commercial use of the architecture (Section 2.4).

2.1 "Technical Modularity" versus "Strategic Modularity"

Sanchez (2013) observes that although many products today exhibit some degree of modularity in their designs, there are important differences in what modularity is intended to accomplish in different firms' product designs, as well as in the development processes through which different firms have sought to introduce modularity into their product designs. On this basis, Sanchez (2013, p.209) distinguishes two different kinds of modularity in product architectures:

Technical modularity exists when at least some interfaces between components in a product design have been specified to allow the substitution of two or more component variations into the design without requiring compensating design changes in components "on the other side" of the interfaces. Technical modularity is often created through routine engineering processes that seek to reduce the development cost of a new design by re-using pre-existing or "industry standard" component designs and/or interface specifications. For example, engineering designers often adopt industry-standard bolts and bolt patterns for connecting various kinds of components, and industry-standard electronic interfaces (like USB interfaces) for connecting digital devices.

By contrast, *strategic modularity* is created through a strategically motivated architecture development process in which the strategic partitioning of the architecture into functional components and the specification of the interfaces between components are both designed to create specific forms of *strategic flexibility* in the product architecture (Sanchez 1995). For example, the component structure and interfaces in an architecture may be designed with a primary objective of allowing a wide range of component variations to be freely used in configuring a strategically desired range of product variations.

The MDRs that we elaborate here apply to firm processes whose intention is to create strategically modular product architectures with specific forms of strategic flexibility intended to directly support a firm's product strategies. Note also that the MDRs that we elaborate below are not intended to describe all the various ways that firms have tried to develop modular product architectures. Rather, the MDRs elaborated here are *normative rules* for ordering the strategic, organizational, and managerial processes that we propose are essential to the successful development of strategically-motivated modular architectures.

The normative MDRs proposed here are derived both from modularity theory and from observations and analyses of successful and unsuccessful attempts to develop modular architectures in a wide variety of firms an industries.[2] This research suggests that very few firms are likely to recognize the need for a broad new set of rules for managing modular development processes like the MDRs we elaborate here. Moreover, even fewer firms are likely to have the managerial and organizational capacity to implement modular development processes that adhere to these rules. However, such firms and processes do exist, as we note below, and we suggest that these firms' successes in creating and using modular architectures lend support to the validity of the MDRs we elaborate below.

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[2] The MDRs that we elaborate here are drawn from more than 25 years of "real-time action research"[2] into numerous firms' processes for creating modular product architectures in the automotive, aircraft, consumer electronics, information technology, manufacturing equipment, office equipment, home appliance, personal health care, medical equipment, food confections, financial services, health services, and travel industries (Sanchez 1995, 2000, 2013, and 2015), as well as from multi-year longitudinal studies of modular development processes in a number of Japanese firms (Shibata et al. 2005; Shibata 2009).

2.2 Modularity Design Rules: Prior to Starting Component Development

Although much research on modularity has been focused on the processes firms use to develop components for their modular architectures (Baldwin and Clark 2000, Sanchez and Mahoney 1996), our research suggests that component development processes actually occupy a relatively late and predictable stage in successful processes for creating modular architectures. As we elaborate below, once the strategic objectives, strategic partitioning of components, and interface specifications for a new modular architecture have been decided, the technical development of components for a new modular architecture may not only be undertaken concurrently, but should also be a fairly routine exercise.

We therefore begin this discussion by elaborating the MDRs that apply to the key strategic, managerial, and organizational processes that need to be undertaken in order to define adequately the strategic objectives for a new product architecture -- and that therefore must precede and then guide processes for developing the components for a new architecture.[3]

MDR No. 1:

A new modular architecture must be developed using only proven component designs whose system behaviors are well understood and whose interfaces can therefore be reliably specified.

We begin our list of MDRs with one of the least understood rules for developing modular architectures. A modular architecture is *modular* precisely because it uses component designs that are technically independent (or "decoupled" from) other component designs in the architecture. In order to technically decouple component designs within an architecture, a firm's developers must know how each kind of component will behave when used in the intended product architecture – i.e., the *system behaviors* of each component. Only when a component's system

[3] The numbering of the MDRs is intended to provide a way to refer to specific MDRs in our discussion. It is not intended to denote a strict sequential order of application of the MDRs in a modular architecture development process. In fact, most of the MDRs apply through more than one stage of development, and some apply throughout all stages in the development and commercialization of a new modular architecture.

behaviors are well understood can developers define interface specifications for the component such that introducing a range of variations of the component into the architecture will not require compensating changes in the designs of other components in the architecture. This technical decoupling of components confers a number of strategic benefits that are fundamental to modular architectures, including the ability to develop components concurrently, resulting in faster development times, and the ability to "plug and play" components within a modular architecture -- i.e., to substitute a range of component variations freely within an architecture to configure new product variations (Garud and Kumaswamy 1995, Sanchez 1995).

Defining interfaces that enable technical decoupling of components within a modular architecture cannot be achieved with new, unfamiliar kinds of components whose system properties are not yet well understood (e.g., components based on new, unproven technologies). Thus, a bedrock principle of modular development processes is that new modular architectures should only incorporate components whose system behaviors (in the inteded type of product architecture) are already well understood -- and whose interfaces can therefore be reliably specified.

A common misunderstanding about MDR No. 1 is the belief that restricting development of modular architectures to incorporating only well-understood, proven component designs will limit the ability of firms to introduce innovative new products with new technologies embodied in new kinds of components. This misunderstanding overlooks the highly disruptive effects and consequential delays that result in conventional development processes when a firm tries to develop an architecture that includes technologically new components whose interfaces cannot be reliably specified. Research has shown that as much as 80% of total development time can be expended in repeatedly redesigning other components as errors and omissions in the evolving interfaces for unproven component designs are discovered during development (Sanchez and Collins 2001).

By contrast, when technically new components are developed and proven "off line," as proposed formally in MDR No.2 below, then such well-understood components with reliably specifiable interfaces can be introduced into next-generation architecture development projects. Studies have shown that some firms have been able to radically accelerate their overall innovation processes by "fast cycling" through rapid development of successive generations of new architectures -- a process that is possible only when each new generation of architecture incorporates technically new components only *after* their system behaviors have been adequately investigated and reliable interfaces can be specified (Sanchez and Mahoney 1996; Sanchez 2004).

MRD No. 2:

D*evelopment of new technologies and new types of component designs based on new technologies must be carried out independently of and prior to their use in a new modular architecture development process.*

For the reasons stated under MDR No.1 above, firms should not try to resolve technical uncertainties about new kinds of components as part of modular architecture development processes. Rather, new kinds of components should be investigated and developed through parallel, decoupled component development processes.[4] These "off-line" development processes should be focused on developing components for next-generation and future-generation architectures identified through a firm's strategic planning and capability development processes (Sanchez 2012).

In effect, adopting modular architecture development processes requires a key change from the traditional processes linking research and development (R+D) and new product development (NPD), as suggested in **Figure 1**. Instead of letting development of new architectures include processes for developing new kinds of components for which research has only provided "proof of concept," modular architecture development processes require that new kinds of components suggested by "proof of concept" from R+D should then be developed "off line" in parallel development processes until their system behaviors are understood and interfaces for each new type of component can be reliably specified ("proof of

[4] See discussion of "Decoupled Architectural Learning" from Figure 2(c) in Sanchez and Mahoney (1996), p71-72.

component”).

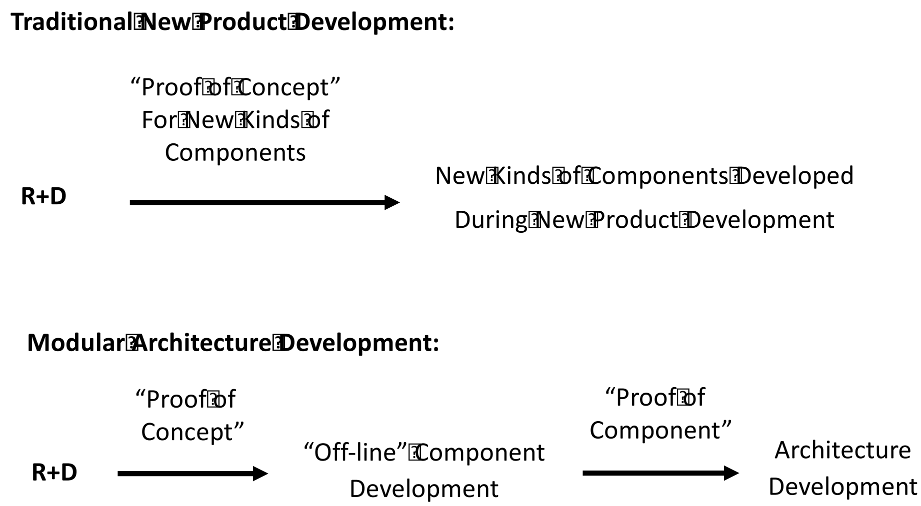

Figure 1: Traditional *versus* Modular Processes for Developing New Kinds of Components

Once new kinds of component designs have been developed and their system properties determined with confidence, the new component designs and their attendant interface specifications can be released into a "design library" of proven component designs that are then available for use in developing next-generation modular architectures.

MDR No.3:

A firm's strategic and technical managers must determine through joint consultations the functionalities and other desired attributes to be provided by a new modular architecture.

Because a modular architecture is essentially a technical creation with a strategic mission, technical managers and strategic managers must work closely together to define next-generation modular architectures. The functionalities and attributes that are strategically desired from a new modular architecture must be communicated by strategic managers to technical managers, who must in turn provide strategic managers with their assessments of what functionalities and attributes can be provided by the current design library of proven component designs available to the firm in developing a next generation architecture. Through an interactive dialogue, strategic and technical managers must jointly decide the components and interfaces that can reliably be used in the new architecture and therefore the resulting functionalities and attributes the new architecture can provide. These consultations between strategic and technical managers constitute the essential first step in initiating a new modular architecture development process.

MDR No.4:

Strategic managers must provide technical managers with a clear prioritization of the strategic benefits sought from a new architecture.

A number of strategic benefits may be obtainable from a new modular architecture, including increasing product variety (by substituting component variations), rapidly upgrading product performance (by technologically upgrading key components), reducing production costs (by using industry standard and/or common components), reducing development costs (by using components already developed by other firms), and increasing speed to market (through concurrent component development processes, re-using existing components, and/or involving more partners in developing new components), among others. While it may well be possible to obtain several or all of these benefits of modularity to some degree in a single architecture, technical constraints are likely to require trade-offs to be made among potentially available benefits in developing a new architecture.

In order for technical managers to know how to *strategically optimize* a modular architecture during development, strategic managers must provide technical managers with a strategically-prioritzed ranking of the modularity benefits to be sought from a new architecture. Without a clear set of priorities from strategic mangers, any technical trade-offs that technical managers may be forced to make during development are unlikely to be strategically coherent or to result in a new architecture that can provide the kind and degree of strategic benefits sought from the next-generation architecture.

MDR No. 5:

Once strategic managers commit to a given slate of strategic objectives and priorities for the various functionalities and other attributes to be provided by a new modular architecture, the strategic objectives and priorities must be "frozen" and not allowed to change during the ensuing architecture development process.

Allowing the functionalities and performance levels to be delivered by a new product architecture to be a "moving target" has been shown to be highly disruptive to any product development process, whether modular or non-modular. To preserve the key advantage of using concurrent and distributed development processes for components in developing modular architectures, changes in the strategic benefits desired from a new architecture cannot be allowed after development of a new architecture has begun. Instead, firms should develop an ability to keep up with changes in market requirements by “fast cycling” through successive generations of modular architectures, each of which can be developed relatively quickly when goals for each new architecture are not allowed to change during development (Sanchez 2013, 2015).

MDR No. 6:

Strategic and technical managers must jointly agree how the new modular architecture will be "strategically partitioned" into functional components.

The way in which a new architecture is decomposed into functional components will significantly affect the kinds of strategic benefits a modular architecture can provide. Most fundamentally, components that will be sources of perceived variety in differentiating products should be kept separate and technically decoupled from other components, so that design variations of those components can be developed and freely introduced into a new architecture. By contrast, components whose functionalities don't have to change may become "cost drivers" when using common components across all or many product models may lead to economies of scale or increased buyer power. In some cases, common components may be combined into subassemblies of "core components" or even integrated components designs that combine several functions.

Thus, once the strategic benefits to be sought from a new architecture have been clearly prioritized, technical managers must evaluate and then communicate to strategic managers the extent to which alternative ways of strategically partitioning the new architecture into functional components would affect the new architecture's ability to deliver the prioritized strategic benefits sought from the architecture -- and at what cost of development and production. Strategic and technical managers must then agree on the optimal approach to partitioning an architecture into functional components, given current strategic objectives and technical constraints for the next-generation architecture.

MDR No. 7:

Interfaces between the components in a modular architecture must be defined to allow the substitution of a strategically desired range of component variations into the architecture -- without requiring compensating changes in the designs of other components in the architecture.

The primary emphasis in conventional NPD processes is typically on developing new components, while the specification of workable interfaces between components is often treated as a relatively unimportant (or "uninteresting") technical detail. As a result, interfaces between components are often allowed to “evolve as needed" during conventional NPD processes or are simply deferred to the last stages of a development process.

In modular architecture development processes, however, interfaces between components must be fully specified *before* beginning development of specific component variations for a new modular architecture. Both the ability to develop initial component designs in parallel (concurrent component development) and subsequently to design component variations that can be freely substituted into an architecture depend on having stable, fully specified interfaces for the architecture.

In some cases, a firm may be able to use an "industry standard" interface that allows a broad range of readily available component variations to "plug and play" in a new architecture, such as a HDMI interface on a visual display and other electronics devices (Sanderson and Uzumeri 1997). Alternatively, a firm may design a set of proprietary interfaces that allow a range of proprietary and/or industry standard components to be used in its architecture, such as Apple has often used for connecting video devices to its laptops.

While even simple interfaces may enable a wide range of component variations to be introduced into an architecture, there are always technical limits to the range of component variations that can be used with any interface. Thus, strategic and technical managers must agree on the range of component variations to be accommodated by each interface in an architecture before specifying the interfaces to be adhered to throughout component development processes.

2.3 Modularity Design Rules: During Detailed Component Development

As suggested earlier, if MDRs No. 1 to No. 7 have been followed in the architecture development process leading up to the launch of detailed component development, then the processes for developing specific component design variations for a new architecture should become relatively routine. However, achieving the strategic benefits sought from a modular architecture, both during and after development, depends on a firm's ability to maintain two critical forms of *organizational discipline* during detailed component development processes, as addressed by MDRs No. 8 and No.9 below.

MDR No. 8:

The specific strategic partitioning of a new architecture into functional components decided prior to beginning detailed component development must be strictly followed throughout the component development process.

The strategic partitioning of a new architecture into functional components prior to beginning development of the components for the architecture (see MDR No. 6) is intended to provide a component structure that best supports the intended strategic uses of a new architecture. While one might hope that component developers are fully aware of and respect the strategic reasons for a particular strategic partitioning, that may not always be the case in every organization. It is possible (and the authors have indeed observed) that well-intended component designers may take it upon themselves to change the way a new architecture has been strategically partitioned, usually for what appear to them to be eminently sensible "technical reasons."

Once the strategic partitioning of the architecture into functional components is agreed, however, any changes in the component structure of the new architecture would be highly disruptive to ongoing component development processes -- for the same reasons stated under MDR No. 5 for freezing the strategic benefits to be sought from a new architecture. Thus, *strict organizational discipline* is required to assure that the strategic partitioning of components agreed by strategic and technical managers prior to the beginning of detailed component development is in fact the set of components that developers actually develop.

MDR No. 9:

Once the interfaces are specified for the components in a new architecture, the interfaces must be frozen and not allowed to change during ensuing processes for detailed development of specific component designs for the new architecture.

A modular architecture is a *system of components* in which the interfaces that are specified between components will largely determine whether the components function together reliably. If not fully and properly specified, the interactions between the components in any system may generate aberrant behaviors.[5] As a result, even simple and seemingly innocuous changes in interface specifications during or after development of detailed component designs may create unanticipated, unintended, and usually undesired changes in the ways the components interact within the architecture.

While it is common practice in conventional NPD to allow changes in interfaces between components during component development, the concurrent and possibly distributed development of components in a modular development processes

[5] Sanchez (1999) identifies 8 kinds of interfaces to be specified in physical product architectures, with closely analogous kinds of interfaces in process architectures and organization architectures.

depends on maintaining a consistent set of interface specifications that assure a stable technical environment for developing the component variations intended for a new architecture.

A further, very important strategic benefit of strictly adhering to initial interface specifications during detailed component development is that doing so will quickly reveal how capable an organization is of specifying interfaces that will enable all the components in a new architecture to perform as intended. When interfaces can be changed by developers during component development, it becomes highly problematic, if not impossible, to determine whether developers have been able to adequately define the interface specifications needed for a new architecture at the beginning of a modular architecture development process. Thus, requiring developers to specify and then adhere strictly to interfaces throughout detailed component development provides a key means for managers to evaluate the technical capabilities and commitment of their organization's developers.[6]

2.4 Modularity Design Rules: After Component Development

Two aspects of modular architectures are also critical to maintain after components have been developed and a new architecture has been put into commercial use, as addressed by MDR No. 10 below.

MDR No. 10:

The strategic partitioning and interface specifications used to create a new product architecture must be maintained throughout the period of commercial use of the architecture.

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[6] The visibility into developers' capabilities that results from requiring developers to fully specify and adhere to interfaces during detailed component development processes may be seen as threatening by some developers, who may seek to resist fully specifying an freezing interfaces in various ways, including through claims of "impossibility." In such cases, it may be useful to keep in mind that "impossibility" results from a lack of either knowledge or volition. If a developer genuinely lacks the knowledge to specify the interfaces for a new component, then the component should be investigated further through the "off line" development process for new kinds of components. If the "impossibility" appears to be volitional, however, managers may need to seek to achieve a closer alignment of the motivation of the developer with goals of the organization.

Once a new architecture is developd and put into commercial use, organizational responsibility for the architecture is often transferred from development engineers to engineers charged with "maintaining" the architecture. Unless this new group of engineers is fully informed about the strategic purpose for the architecture and the strategic reasons behind the architecture's strategic partitioning and interface specifications, they may begin to make well-intended technical changes to the architecture's component structure and/or interfaces. Such changes may, however, have very undesirable consequences.

Maintenance engineers may try to make the same kinds of "cost-saving" changes to the component structure of an architecture that component developers sometimes want to make during development. For example, maintenance engineers may decide that integrating components that have been decoupled for strategic reasons would save cost or improve performance. However, this and other kinds of changes to components and their interfaces could lead to unexpected behaviors of components within the architecture, or could limit the ability to introduce component variations during the commercial lifetime of the architecture. Similarly, changes intended to "simplify" or otherwise modify interfaces may impose limitations on the configurability of an architecture already in commercial use. Thus, as a general rule, managers should monitor the activities of engineers responsible for maintaining an architecture to make sure that no changes are made to the original components or interfaces, lest they affect the reliability or configurability of the architecture.

Moreover, free-lanced changes to interfaces during the commercial lifetime of an architecture may make it impossible for both strategic and technical managers to ascertain how effective the originally specified interfaces for the architecture have been in delivering the configurability and reliability they were designed to provide. As Toyota has learned and incorporated into its Toyota Production System, the ability to determine exactly what was done by whom -- and then to link that information to the subsequent performance of a finished product -- is essential to continuously improving assembly task definitions and in identifying individual workers in need of more training (Spear and Bowen 1999). Analogously, the ability to link the component designs and interface specifications provided by specific developers to the subsequent performance of the architecture is essential to identifying individual and organizational capabilities that need to be improved in developing effective modular architectures (Sanchez 2000, 2005; Sanchez and Collins 2001).

3. RENAULT-NISSAN ALLIANCE'S TRANSITION TO A "COMMON MODULE FAMILY" MODULAR ARCHITECTURE

We now provide an overview of a multi-year longitudinal study by this paper's co-authors of the Renault-Nissan Alliance's (RNA) development of a modular "Common Module Family" (CMF) architecture.[7]

The ambitious strategic objectives articulated by RNA strategic managers for the CMF architecture were two-fold: First, the CMF architecture was to achieve a targeted 30% reduction in per-vehicle costs through extensive use of common components across model variations. Second -- and equally important -- the CMF architecture was to enable the configuration of more than 50 Renault and Nissan branded product models with distinctive brand identities and readily apparent functional and stylistic differences. Our study examined both the modular vehicle architecture developed by RNA and the managerial and organizational processes implemented by RNA senior management to support the transition from conventional NPD to modular development processes.

In the following discussion, we summarize the strategic motivation for RNA to adopt the CMF modular architecture and the changes in management processes and

[7] The longitudinal case study whose key findings are reported here included extensive interviews with key Nissan and Renault-Nissan Alliance (RNA) executives and managers between November 2012 and August 2013, with periodic follow-up interviews through 2017. We would like to thank in particular Mr. Hideyuki Sakamoto, at the time Corporate Vice President of Nissan Motor Co., Ltd., and Mr. Hiroyoshi Yamamoto, at the time General Manager in charge of the RNA executive office, for their generous cooperation in gathering detailed information on the processes initiated by RNA for the development of the CFM modular architecture, and in confirming our interpretations of data provided by sources within RNA. We also thank Mr. Yamamoto for reviewing several draft versions of the findings reported here.

organization structure undertaken by RNA to support development of the CMF modular architecture.

3.1 Modularity in RNA's Global Strategy

The global automotive industry has historically faced both increasingly substantial sunk costs for product development and production tooling, on the one hand, and rapidly rising demand for more differentiated models and more frequent introductions of new models, on the other. Given these two conflicting pressures, it was perhaps inevitable that at least some major automobile producers would turn to modular product architectures to seek new possibilities for reducing costs while increasing product variety.

The modular "platform" architectures adopted by Volkswagen in the early 1990s, for example, both sought and achieved substantially lower product costs while also adding new product models and increasing the "refresh rate" of its platform models, as has been extensively reported (Pandremenos et al. 2009). The Renault-Nissan Alliance, formed in March 1999 by the French producer Renault and the Japanese producer Nissan, pursued similar objectives through an ambitious initiative to create a new modular vehicle architecture.

In February 2012, Mr. Carlos Ghosn, then President and Chairman of RNA, announced the launch of a "4+1 Common Module Family" (CMF) program whose general intent was to create a modular vehicle architecture that would achieve substantial vehicle cost reductions while providing an expanded range of models for the Renault and Nissan brands. The "4+1" refers to the strategic partitioning of the new CMF modular vehicle architecture into four large body modules (engine compartment, front underbody, rear underbody, and cockpit) and one electrical/electronics module (also known as the electronic vehicle architecture, or "EVA").

As suggested in Figure 2, the indicated variations in the four main body modules could be "mixed and matched" to produce visually distinct models within four families of vehicle types, identified as multi-purpose vehicles (MPVs), sport-utility vehicles (SUVs), conventional sedans (SEDs), and smaller hatch-back vehicles (H/Bs). The variations in the combinable big modules shown in Figure 1 can in principle provide $2 \times 3 \times 3 \times 3 = 54$

distinct body shapes for different product models produced under the Renault and Nissan brands.

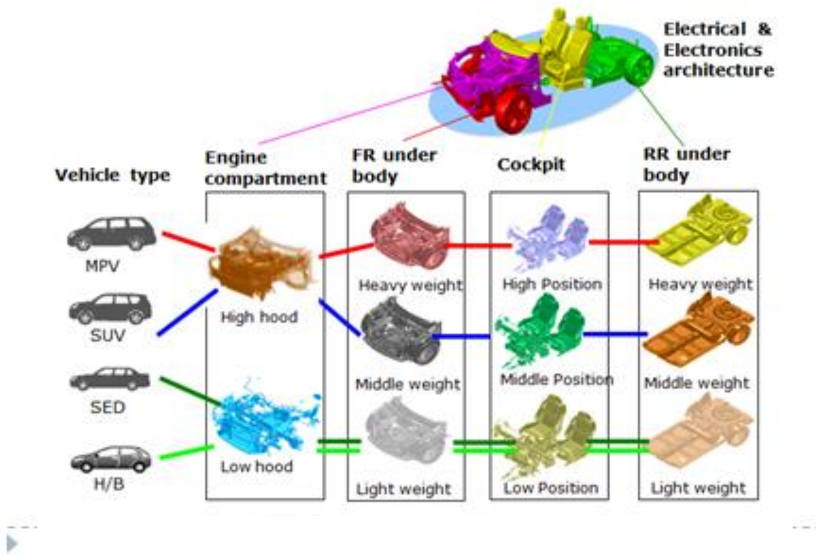

Figure 2: "Big Modules" in "Common Module Family" (CMF) Architecture
(Source: Renault-Nissan Alliance)

The specific strategic objectives for the first stage of RNA's conversion to the CMF modular architecture were (i) to achieve at least a 30% reduction in per vehicle production costs through large-scale production and assembly of common body modules and components, while (ii) also enabling configuration of an expanded range of Sport-utility vehicles (SUVs) vehicles with distinctly different designs. The cost savings to be achieved through cost reductions for common modules and components were then to be invested in improving the environmental and safety performance of RNA's vehicles -- two aspects of vehicles that were becoming increasingly important sources of competitive advantage in major automotive markets around the world.

The first CMF-based model introduced to the market was the Nissan X-Trail that began mass production in the autumn of 2013. Subsequently more than 1.6 million CMF-derived vehicles (composed of two types of Nissan X-Trail vehicles and

10 Renault SUV models) were brought to market by mid-2017. The CMF architecture achieved at least 56% component commonality (cost basis) between Renault and Nissan SUV vehicles -- and thereby realizing the targeted 30% reduction in production costs per vehicle, as well as substantial reductions in development cots -- while maintaining the distinctiveness of Renault and Nissan vehicle designs and expanding the number of distinct product models available to each firm in the RNA global product portfolio.[8]

3.2 Launch of the CMF Initiative

The CMF initiative announced by Carlos Ghosn in February 2012 was conceived in September 2009 jointly at Renault's design centers near Paris, France, and Nissan's R+D center near Tokyo, Japan. Much of the first year of the initiative was spent identifying how the two firms' development structures and processes would have to change from their conventional, model-focused development processes to a new modular architecture-focused process that could serve the market strategies and incorporate the technical resources of the two companies working together.

The development of new management and organization processes for developing the CMF architecture was driven by the pointed and ongoing monitoring of the project's progress by Carlos Ghosn personally and by the assignment of specific responsibilities for the CMF architecture initiative to several several senior executives within both Renault and Nissan. Moreover, selection of staff from various areas of the two companies for participation in the CMF project was communicated as an important form of personal recognition and as an opportunity to play a key role in shaping the RNA of the future. All told, just over 200 people were selected

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[8] During the CFM architecture development process, RNA managers came to believe that the "optimal extent of commonality" of components to be sought through the CFM architecture would lie somewhere between 50% and 75% commonality of components in all vehicle models derived from the CFM architecture. Their conclusion was that more than 75% component commonality would result in vehicles that would not be adequately differentiated from each other in the market, while less than 50% component commonality would not achieve the full extent of component cost reductions available through the CMF architecture.

and charged with creating not just the first CMF for RNA -- but also with creating the new management and organizational processes that would unite the two companies in defining and developing the CFM architecture that would be the common basis for their future strategies.

3.3 New Organization Structures and Management Processes for Strategic Partitioning of the CMF Modular Architecture

As we have noted in Section 2, once the prioritized strategic objectives for a new modular architecture have been defined, the first step in the modular architecture development process is to determine the most effective strategic partitioning of functional components to support the prioritized strategic objectives for the new modular architecture. The CMF project team recognized that deciding the most effective strategic partitioning of the architecture would require extensive consultations between the two firms' marketing and technical managers -- but that no structures or processes existed within Renault or Nissan for jointly making such a critical decision. Beginning in September 2009, the CMF team leaders therefore focused on defining the new organizational structures and management processes that they believed they would need in order to decide how to partition the the CMF architecture.

The CMF team recognized that defining the optimal strategic partitioning of the architecture would require new forms of intensive consultations between marketing staff and technical staff from each of the two companies. The CMF team also recognized that if staff from the two areas of expertise and/or from the two companies could not agree on what partitioning would be optimal, someone would have to have overall responsibility and authority for deciding the strategic partitioning to be adopted.

The organization structure adopted by the CMF team to support the strategic partitioning of the CMF architecture is shown in **Figure 3**. In this structure, the Chief Vehicle Engineer (CVE) is responsible for all the technical aspects of the vehicles configured within the new CMF architecture, while responsibility for market analysis and planning for the vehicles to be derived from the new architecture is vested in the Chief Product Specialist (CPS). Overseeing this structure and its decision process process is the Program Director (PD), who in the absence of agreement between the CVE and CPS, has the authority to interpret the specific market goals for the CMF architecture, to decide the range of vehicles the architecture will support, and to set the number of vehicle variations to be leveraged from the architecture. These three senior managers (drawn from both Renault and Nissan) were jointly charged with managing both the development of the CMF architecture and the subsequent configuring of individual models within the CMF architecture.

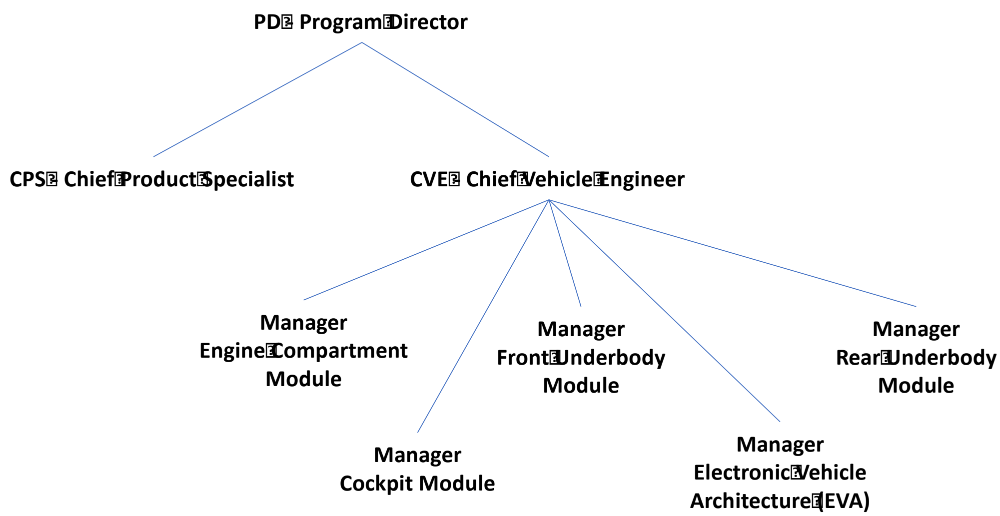

Figure 3: Organization Structure for Strategic Partitioning and Development of CMF Architecture
(Source: Renault-Nissan Alliance)

Using this structure to carry out essential consultations, the CMF management team eventually decided that an architecture strategically partitioned into four big body modules and one electrical/electronic module would most effectively serve and support the strategic priorities for the new architecture (See Figure 2). A "module manager" was then appointed for each of the 4+1 big modules. The module managers were made responsible for the design and development of their module, for subsequent performance improvements for their module, and for the compatibility of all the components used within their module.

The 4+1 "big modules" adopted by the CMF team as the first level of strategic partitioning of the CMF architecture each contained significant numbers of components. To achieve the desired scale economies from extensive use of common components, the CMF team had to further strategically partition each of the 4 big module to define the specific kinds of components to be used in each module and to identify which components could be used in common across product models in the CMF architecture. The CMF team soon realized that three issues would have to be managed in deciding which components within each CMF module would be used in common across all or many product models and which would be specific to individual models or brands.

First, the market requirements affecting a number of components were quite different in Renault's and Nissan's main markets of Europe, Asia, and North America, so trade-offs would have to be made between using standard components across the three regions to increase scale and reduce production costs, on the one hand, and allowing region-specific component variations to locally adapt vehicles to meet regional market preferences and requirements, on the other. Second, for many kinds of components Renault and Nissan had historically used different kinds of design solutions (referred to as "Technical Policies" within Nissan). As a result, the two firms had different ways of locating and otherwise integrating various components within their respective vehicle architectures. Third, each company had their own distinctive ways of designing major elements of their vehicle architectures, such as designs of the "crash cage" for protecting passengers in a collision, the general arrangement of the engine compartment, and the positioning of driver and passenger seats within a vehicle.

In some instances, differences in the component functionalities and design solutions sought by Renault's and Nissan's development staffs could be resolved by purely technical solutions. Nevertheless, some disagreements about component designs reflected underlying differences in marketing objectives, production capabilities, or other factors that could not be resolved by technical staff alone. Each component whose functionality and design could not be agreed between the two firms or between marketing and technical staffs was therefore identified as a "Road Block" ("RB" for short). Identified RBs were, in effect, the manifestations of significant technical or strategic differences between two companies that would have to be resolved by senior managers before the two companies could begin to create a vehicle architecture with substantial component commonality. The CMF team realized that new management processes would have to be created to make decisions about the common components to be used by the two companies and remove each Road Block to creating the CMF architecture.

Within a few months, more than 800 component RBs were identified across the 4+1 big modules. To resolve the 800+ RBs, senior RNA management established a new management process composed of a Joint Steering Committee (JSC] for each of the five big modules (see **Figure 4**). Each JSC was composed of senior marketing and technical managers from both firms and reported directly to the senior executives of both firms. The JSC for each big module then assigned CMF team members and other RNA staff with relevant marketing and technical expertise to work together in "Upstream Strategic Focus Teams" (USFTs) to resolve each component RB. In all, 76 USFTs were created to resolve Road Blocks for specific types of components, and more than 1500 employees from Renault and Nissan participated in 76 USFTs focused on resolving component RBs.

Importantly, the JSC promulgated a "new rule" that no development work on any component could begin until all RBs for that component had been resolved and approval for the component type had been received from the JSC responsible for the part of the CMF architecture that incorporated each component. For their part, the JSCs coordinated with the Cross-Company Team of senior executives from both companies who were tasked with assuring that each technical solution accepted for an identified RB would be effective in supporting each firm's marketing strategy.

RNA senior management also established Joint Steering Committees (JSCs) staffed by senior managers from the two firms to resolve cross-company issues arising in the detailed development of each of the 4+1 modules, as well as a JSC to coordinate the two firms' marketing plans for models derived from the first CMF architecture.

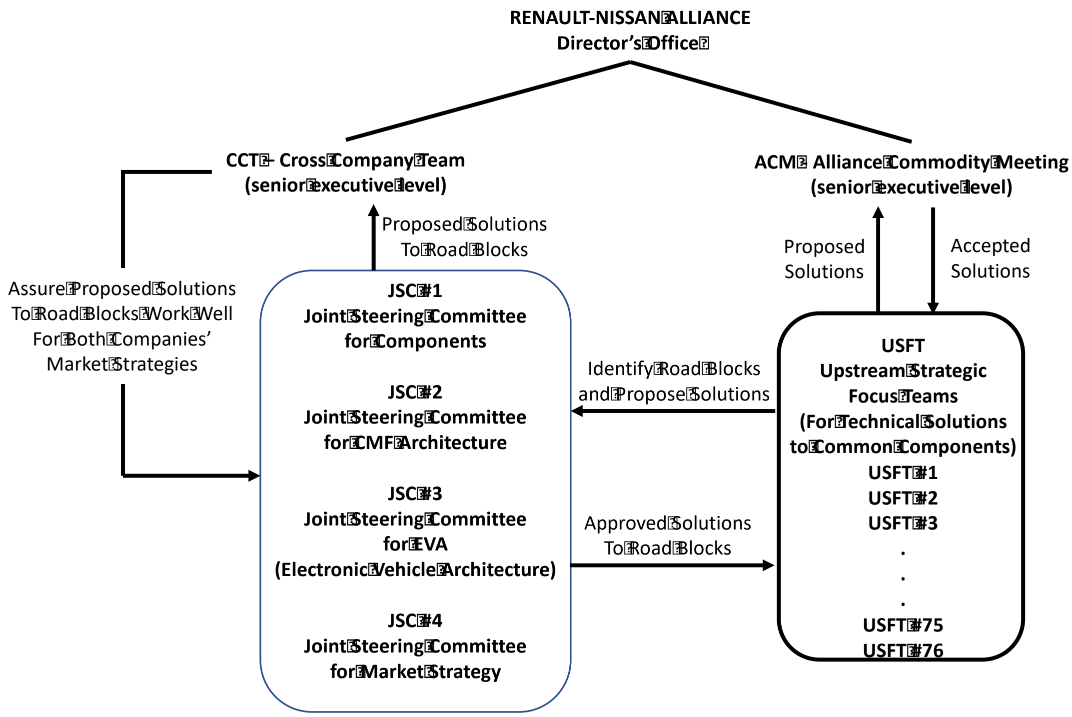

Figure 4: Management Process for Resolving "Road Blocks" in Development of CMF Architecture
(Source: Renault-Nissan Alliance)

Using this new organizational structure and management process, the full list of 800+ component RBs and a number of big module and marketing issues were resolved in the 15 months between September 2009 and December 2010, after which full-scale development of components for the CFM architecture was allowed to proceed.

4.4 New Processes for Involving Suppliers in CMF Architecture Development

Developing the CMF architecture and producing a range of CMF vehicle models with high levels of component commonality required significant changes in both Renault's and Nissan's relationships with their suppliers. Prior to the development of the CMF architecture, both firms developed and purchased components for individual vehicle models. By standardizing on common components to be used in all or many vehicle models, the production volumes for each component used in the CMF architecture increased dramatically -- from typical single-model component lots of 50,000 to 100,000 units to more than 1,700,000 units for components used in all CMF models. The shift from small lots of many component variations to large lots of relatively few common components meant that RNA's interactions with its suppliers had to change from arm's-length contracting with many suppliers to close cooperation with fewer but larger suppliers.

Recognizing the need for new kinds of interactions and processes with suppliers, the CMF team began to build new kinds of relationships with their suppliers -- at both strategic and operational levels -- in the early stages of CMF development. The cooperative relationships the CMF team developed at the strategic level involved sharing sensitive market information and cost targets with suppliers, so that suppliers could make better decisions in allocating their own resources to development and production activities that would be effective in supporting the CMF architecture.

Similarly, at the operational level, closer cooperative relationships were built so that the CMF architecture development process could both provide more complete information to suppliers and more effectively draw on the expertise of suppliers. For example, suppliers received much more information than previously about projected production volumes and expected model variations, and were in turn asked to propose component designs that would increase possibilities for component sharing across anticipated models.

3.5 Processes for Specifying and Controlling Interfaces During and After Development

As in any modular architecture, the interfaces between the CMF 's 4+1 big modules and between each module's respective set of components determined the ease with which -- and thus the extent to which -- the big modules could be mixed and matched to configure different product models, as well as the extent to which the components used in each module can be used in common across product models. Accordingly, the 76 USFTs created to develop suitable modules and components for the CMF architecture were also charged with specifying interfaces for their module or component that would enable as many components as technically possible to become common components within the CFM architecture. For example, the CMF architecture defined common interfaces for attaching all roof panels, but some roof panels that were important in differentiating specific product models could be designed later as long as they conformed to the roof attachment interface.

The USFTs were also responsible for assuring that the interfaces specified for each CFM module and related components remained "frozen" (standardized) and were adhered to during module and component development processes. Given the deep experience and accumulated technical knowledge in both Nissan and Renault relevant to the 4+1 modules and related components, computer simulation technology could be used both to develop modules and components and to check the suitability of the interfaces between modules and components during development.

4. MODULAR DESIGN RULES IN RNA'S DEVELOPMENT OF THE CMF MODULAR ARCHITECTURE

RNA's success in developing its new Common Module Family modular architecture was remarkable in a number of respects.

For one, the highly successful CMF development process was the result of a *first effort* by Renault and Nissan to create a modular architecture that would serve the diverse requirements for their individual brands of vehicles in the Asian, European, and North American markets. Moreover, the CMF project was not a small-scale "pilot project" intended to test the feasibility of using a common modular architecture for the two firms' products. On the contrary, the CMF project was specifically charged with creating a common vehicle architecture that would be the basis for projected production of nearly two million vehicles whose costs of production would run into tens of billions of US dollars. In addition, the CMF project had to find a way to bring together two firms with very different traditions in vehicle development, design, and marketing -- and somehow find a way to enable the two firms to work together in creating a common vehicle architecture that would serve the interests of both firms well.

Perhaps the daunting nature and scale of the task facing the CMF team -- coupled with the lack of any pre-existing management processes or organizational structures in either company for accomplishing such a task -- left the CMF team no choice but to invent a radically new way of working in order to begin development of a common modular architecture. In any event, for this discussion the most noteworthy aspect of the management processes and organization structures implemented by RNA senior management and the CMF team is how extensively they embodied the Modular Design Rules that we propose in Section 2.

At the launch of the CMF project, for example, RNA senior management provided a clear statement of prioritized strategic goals for the CMF architecture (MDR No. 4). Moreover, the strategic goals given by top management for the CMF architecture remained the same throughout the CMF development process (MDR No. 5).

To achieve the strategic objectives of substantially reducing unit costs through use of common components while maintaining brand distinctiveness and requisite product variety, the CMF team was composed of both marketing strategy and technical staffs that worked directly with each other and that were supported by and reported directly to RNA's strategic-level managers (MDR No. 3).

The first development task undertaken by the CMF team was deciding the component structure (strategic partitioning) of the CMF architecture to be developed (MDR No. 6). In order to provide a stable technical structure for the new architecture to be developed, the strategic partitioning of the CMF architecture into 4+1 "big modules" and then into the components that would be used within each module was maintained throughout the CMF development commercialization process (MDR No. 8).

After the strategic partitioning of the CMF architecture was decided, the interfaces between the 4+1 modules and between their respective components were defined and frozen to enable concurrent development of components (MDR No. 9). The defined interfaces were maintained through the component development phase both for standard components that would be used across many or all product models within the CMF architecture and for component variations that would be "mixed and matched" within the CMF architecture to create product variations (MDF No. 7).

Once the strategic partitioning of the CMF architecture was accomplished and the interfaces between 4+1 modules and between their respective components were defined, then -- and only then -- were detailed component development processes allowed to begin. This rule applied to both components for the initial vehicles models to be derived from the CMF architecture and for future components for new models to follow. Only after completing development of the 4+1 modules and related components were various vehicle models configured using the fully developed 4+1 modules and related components for the CMF architecture (MDRs No. 1, 2, and 10).

We also note that throughout the CMF architecture creation process, RNA senior management demonstrated their willingness to perform the top management leadership roles that we suggest here are essential to achieving success in any modular architecture development process: RNA's senior and middle managers were willing to learn a significantly new way of setting product strategies and managing development processes. They were willing to become personally involved in directly monitoring and supporting the modular architecture initiative. They were willing to undertake significant change in their respective organization's management processes and organizational structures in order to implement the new modular way of working. And they were willing personally to bearing the risk of supporting a new modular architecture development process that would lay the foundations for their two companies' futures.

6. CONCLUSIONS

The normative model of Modularity Design Rules for modular architecture development processes that we elaborate here reflects nearly two decades of theory development and empirical research into modularity strategies and modular architecture development processes (Sanchez 1995, 1999; Sanchez and Mahoney 1996, 2013; Sanderson and Uzumeri 1997; Worren, Moore and Cardona 2002). This research strongly suggests that *successful* modular development processes are fundamentally different from the practices widely used in organizing and managing conventional new product development. They also differ fundamentally from related development models such as "Overlapping Problem Solving" (Clark and Fujimoto 1991), which Sanchez and Mahoney (1996) characterize as essentially an effort to compress and thereby accelerate traditional development processes.

Because modular development processes are a relatively recent evolution in our understanding of how products can be developed, in management research or management practice there is not yet a common, consistent understanding of how modular development processes need to be managed and organized. Baldwin and Clark's (2000) *Design Rules* was an early effort to delve into modular development processes by suggesting that achieving technical decoupling among components in an architecture would be facilitated by decoupling the organizational processes for developing such components.

In this discussion, we have sought to elaborate an expanded notion of "Modularity Design Rules" to present an interrelated set of *rules for management processes and organizational structures* that we suggest must be understood and followed in order to implement processes for successfully developing modular architectures. We have also noted that senior managers have essential roles that they must fulfill in supporting the implementation of modular development processes.

We have also drawn on our study of the Renault-Nissan Alliance successful initiative to create a "Common Module Family" modular architecture to provide some empirical evidence in support of the Modular Design Rules we have proposed. Our case study shows that all ten of the Modular Design Rules that we propose here were in fact recognized as necessary and followed by RNA senior management and the CMF development team in their highly successful development of the CMF modular architecture.

There are obvious limits to what can justifiably be inferred from a single case study, even one reporting such a remarkable achievement as this one does. We therefore do not suggest that the "single data point" that we have reported in our case study provides conclusive evidence in support of our propositions. Rather, we suggest that the empirical contribution of this paper is to add another case study to ongoing research suggesting that successful development of modular architectures requires implementing specific managerial processes and organization structures that should be designed and implemented in accordance with the set of Modularity Design Rules that we propose here for governing those processes and structures.

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