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MODULARITY-AS-PROPERTY, MODULARIZATION-AS-PROCESS, AND ‘MODULARITY’-AS-FRAME: LESSONS FROM PRODUCT ARCHITECTURE INITIATIVES IN THE GLOBAL AUTOMOTIVE INDUSTRY

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Modularity is a design property of the architecture of products, organizations, and interfirm networks; modularization is a process that affects those designs while also shaping firm boundaries and industry landscapes; and ‘modularity’ is a cognitive frame that guides categorization and interpretation of a wide array of economic phenomena. Modularity-as-property and modularization-as-process are deeply intertwined; while modularization processes are ubiquitous and perpetual as engineers and managers seek to understand interdependencies across the boundaries of product and organizational architecture, the extent to which modularity-as-property is achieved must be assessed empirically. The framing of ‘modularity’ affects strategy by prompting a particular dynamic—and directionality—in the interplay between modularity-as-property and modularization-as-process. I analyze product architecture initiatives in the global automotive industry, examining first the industry-level antecedents of the emergent production-based definition of modules and then two firm-level modularity initiatives that both were based on this common definition, but framed their strategies differently. In the first case, a ‘modularity’ frame based on a computer industry analogy resulted in overemphasis on achieving modularity-as-property that created barriers to learning about cross-module interdependencies. In the second case, early emphasis on modularization-as-process yielded quasi-integrated organizational arrangements that facilitated long-term design improvements. Overall, this single-industry case study demonstrates the importance of examining the context-specific antecedents of module definition; the multiplicity of potential barriers to modularity that can lead to persistent integrality; the need for longitudinal inquiry into the ‘mirroring’ hypothesis that pays as much attention to process as to property; and the power of modularity as a cognitive frame, which helps explain divergent findings in modularity research. Copyright © 2013 Strategic Management Society.

INTRODUCTION

Modularity is a design property of the architecture of products, organizations, and interfirm networks; modularization is a process that affects those designs while also shaping firm boundaries and industry landscapes; and ‘modularity’ is a cognitive frame that guides categorization and interpretation of a wide array of global economic phenomena. Modularity-as-property and modularization-as-

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process are deeply intertwined; while modularization processes are ubiquitous and perpetual as engineers and managers seek to understand interdependencies across the boundaries of product and organizational architecture, the extent to which modularity-as-property is achieved is subject to contingencies and must be assessed empirically. The framing of 'modularity' affects strategy by prompting a particular dynamic—and directionality—in the interplay between modularity-as-property and modularization-as-process.

These three aspects of modularity—property, process, and frame—are frequently entangled analytically, leading to multiple and divergent predictions, contradictory observations, and ambiguous conclusions. For example, is Apple's iPod an exemplar of the cost-saving and innovation-speeding benefits of modular product architecture (e.g., Mudambi, 2008)? Or do its innovations arise from the integration of its elegant hardware design with the iTunes software under a new business model for acquiring music? Understanding how either statement, or both, could be true requires a more multifaceted and context-anchored analysis of these three aspects of modularity.

The confusion about modularity is frequently evident in discussions of its role in globalization processes. When modularity is cited as a driver of the outsourcing that can lead to 'hollowing out' for firms and nations (Herrigel, 2004), what is emphasized are the properties of standardized, commoditized components whose outsourcing allows knowledge to move out of the focal firm or country via a possibly irreversible division of labor. Accordingly, any sign of product modularity may be taken as evidence that a technologically determined path to a disintegrated supply chain (and offshore contract manufacturers who eventually become design rivals of developed country incumbents) is inevitable. Yet the ongoing process of coordination at the organizational interface for outsourced tasks can reveal unexpected interdependencies and lead to (partial) reintegration of component design and/or production into the focal firm or nation (Berger, 2006). Disintegration of product or organizational architectures from globalization is rarely a final destination; fluidity, reversibility, and shifts in strategic logic are the norm.

The interaction between globalization and modularization processes is at once heavily influenced by antecedents—what initiates these processes, what goals are defined, what strategy is being pursued—and highly variable as to outcome, because of the contingent ways in which modularization processes affect the extent of modularity-at-property that is achieved. If globalization initiatives by multinational firms are viewed as quasi-experimental tests of the firm's ability to extend its capabilities into other markets and institutional contexts (or to move tasks outside the firm's boundary to a global supplier via outsourcing) and modularity initiatives are similarly understood as explorations of how best to manage interdependencies across product and organizational boundaries, it becomes clear why the interaction of these emergent learning processes is unlikely to lead to deterministic consequences.

This article proposes grounded attention to the context-specific particulars of modularity, emphasizing these intertwined aspects of property, process, and frame, as remedy to the risks already mentioned. For example, innovation viewed from the modularity-as-property perspective emphasizes higher interdependencies within modules and reduced requirements for coordination across modules that allows focused and autonomous attention to component design by specialized suppliers and leads to more rapid and less constrained innovation (Langlois and Robertson, 1992; Ulrich, 1995; Baldwin and Clark, 2000). Yet a more process-based view of modularity is needed to understand the now-commonplace observation that coordination-and-communication intensive activities can ***precede*** emergence of modular properties and standardized interfaces. When modular properties are viewed longitudinally, i.e., as emergent from a modularization process, they are often revealed to be an *ex post* consequence of integrative forms of organizing rather than the *ex ante* basis for independent organizing (Cabigiosu and Camuffo, 2011; Staudenmayer, Tripsas, and Tucci, 2005; Brusoni, Principe, and Pavitt, 2001).

This challenges the causal assumption that 'product designs organization' (Sanchez and Mahoney, 1996) and means that even when product and organization evolve to mirror each other, the starting point may be an organizational change as readily as a technical or product change (Campagnolo and Camuffo, 2009). Furthermore, while product architectures are often portrayed as moving inexorably from integral to modular as early idiosyncrasies give way to a dominant design (Argyres and Bigelow, 2010), counterexamples can be found in which firms move deliberately from modular to integral product architecture through differentiating innovations that provide advantage over competitors

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(Fixson and Park, 2008). Modularity-as-property and modularization-as-process are so intertwined, so embedded in dynamics of reciprocal feedback, that examination of one without the other is inevitably incomplete; unidirectional views of their relationship can lead to incomplete and potentially distorted conclusions.

'Modularity' as a cognitive frame enters this account as a crucial influence on how the intertwining of modularity-as-property and modularization-as-process unfolds. For example, when a firm frames 'modularity' as a strategy for allowing a supplier to work autonomously on design innovations, by establishing certain product properties, i.e., clearly defined module boundaries and standardized interface specifications, the consequence may be a mutual reduction in coordination efforts that interferes with the learning essential to modularization processes. Managers may develop 'modularity'-as-frame based on the example of another industry's success with modular product and organizational architecture, neglecting to recognize how these architectures differ across industries. The frequent reliance on the personal computer as the exemplar of modularity and harbinger of the future is a case in point. The PC, in its precise mapping of functions to components, open industry-level standard interfaces, and clean correspondence between module and firm boundaries, may be more the exception than the rule (see Jacobides, MacDuffie, and Tae, 2012). Used as the analogy that anticipates these characteristics, in both product and organizational architecture, the computer industry has provided a cognitive frame that overemphasizes achieving modularity-as-property at the expense of attention to what can be learned from modularization processes. Such an analogy conveys the deterministic idea of an inexorable and self-reinforcing logic pointing toward one set of inevitable outcomes—technological, organizational, or both (due to mirroring).

In contrast, the best modularization research avoids determinism by being grounded in close observation of the particulars of a given industry, product, firm, country/region, and/or supplier network (the IBM System/360 computer in Baldwin and Clark, 2000; aircraft engines and chemical engineering in Brusoni, Principe, and Pavitt, 2001; air conditioners in Cabigiosu and Camuffo, 2011; bicycle drive trains in Fixson and Park, 2008; automotive front ends in Fourcade and Midler, 2004; flat panel displays in notebook computers in Hoetker, 2006; mortgage banking in Jacobides, 2005; mobile handsets in Mudambi, 2008). This research reveals that the properties of modularity are layered, can be internally conflicting, and are often incompletely realized; that both costs and capabilities are crucial determinants of when modularization processes will advance to modularity-as-property and when they will not; and that modularization generates dynamics that can move architectures away from, but also back toward, integration.

Here I examine the global automotive industry. While certain industries allow clear characterizations about their technological and organizational architecture (cf. the personal computer industry, as noted earlier), the global auto industry is a complex case that is more difficult to classify. It is exactly these classification difficulties that provide the potential for insight and theoretical advance.

Numerous modularity initiatives in the global automotive industry in recent years have faced unexpected technological and organizational barriers. My goal is to identify what we can learn about modularity and modularization from studying the gap between hoped-for goals versus the reality of what has been achieved in this particular context. I start with a theoretical review to disentangle these concepts of modularity-as-property, modularization-as-process, and 'modularity'-as-frame that are often conflated, so that we can see each one distinctly and in relation to the others. I then apply these concepts as lenses to three different sets of events: first, understanding the idiosyncratic definition of 'module' that has emerged in the auto industry; and second and third, comparing cases of modularity initiatives at Ford Motor Company and Hyundai Motor Company, selected for theoretical contrast. In the discussion and conclusion, I draw out the implications from this single-industry study for future research on modularization and for the global architecture of the multinational firm. I use the computer industry as a foil throughout, not for a full sectoral comparison but rather to highlight the broader theoretical significance of this study of the automotive industry.

THEORETICAL OVERVIEW

The literature on modularity is diverse, large, and difficult to absorb. In this overview, I cover key reference points to orient the reader for the case analyses, emphasizing the distinction (and interrelationship) between modularity-as-property and modularization-as-process. The term 'modularity' is

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often used, in academic literature as well as managerial discourse, to refer to both aspects, a source of much confusion. I distinguish technical property and organizational process, while also arguing that both aspects must be examined simultaneously to understand the antecedents and consequences of modularity and the dynamics of modularization. I treat 'modularity as frame' separately, at the end of this section.

Modularity-as-property

In the classic ideal-typical definition by Ulrich (1995), modularity is a design property of product architecture such that functions have a one-to-one mapping onto physical components and interfaces are specified for ready decoupling. Its conceptual opposite, integrality, is characterized by the absence of one-to-one mapping, i.e. 'one-to-many,' in which multiple physical components fulfill a function, or 'many-to-one', in which multiple functions are fulfilled in a single physical component, in both cases with tightly coupled interfaces. Full modularity decomposes the complexity of a product into fully separable components, such that each component can be developed independently without necessary coordination with other components (Langlois, 2002). In the ideal type, the combination of full modular separability and fully specified interfaces allowing easy interoperability facilitates the reduction of coordination costs and rapid, autonomous innovation.

While conceptually valuable, this ideal-type of modularity fits relatively few products. (That it fits the personal computer quite well is evident from how often this product is used as the prototypical example of modularity; yet as noted earlier, the PC may be more the exception than the rule.) In fact, most products exhibit a combination of modular and integral characteristics. While full decomposition may be essential for complete modularity, it is rarely achieved; instead, efforts to segment a complex system yield near decomposition (Simon, 1981), in which some interdependencies remain across modules, yet many fewer than the interdependencies contained within module boundaries.

Baldwin and Clark define modules in precisely this way, i.e., with interdependencies that are greater within modules than across modules. Baldwin (2008) goes on to describe module boundaries as 'thin crossing places,' a metaphor for the reduced (yet not eliminated) coordination 'traffic' between and among modules. Schilling (2000: 315) notes that all systems are modular to some degree 'since [they] are characterized by some degree of coupling (whether loose or tight) between components, and very few systems have components that are completely inseparable and cannot be recombined.' (By the same logic, all systems are also, to some degree, integral.) For this reason, Fixson (2005) argues that the mix of modular and integral characteristics in a product can be best understood by assessing the degree to which interfaces are coupled or decoupled ***separately*** from the extent of function-to-component mapping.

Furthermore, since each component of a product can also be analyzed as a product with its own components, assessing any characteristic of modularity (e.g., the degree of function-to-component matching; whether elements are tightly or loosely coupled) depends entirely on the level of the product hierarchy that is the focus of inquiry. The result, as Fixson (2005: 351) argues, is that 'a label for the entire product is essentially creating an *average* assessment of the product architecture.' For more precision, the level of the product hierarchy must be specified before assessing the extent of modularity. This is not only a choice for the external analyst. Those agents actively involved in choosing module boundaries and specifying interfaces will evaluate modularity-as-property differently depending on the level where they fix their gaze—whether they are gazing at a component, product, or organization.

I now shift attention from modularity as a noun to 'modularizing' as a verb, in the spirit of Karl Weick's (1969) appeal to scholars to shift their attention from organizations to 'organizing.'

Modularization as process

Viewed through the lens of Simon's idea of near decomposability, modularization is an evolutionary process that is pursued and gradually advanced, but never fully completed, rather than an architectural property that is set as a design goal, achieved, and stabilized. As a process, modularization involves mapping functions to components to create 'thin crossing places' at the module boundary and then setting out to learn and master the remaining interdependencies across modules in order to make sure that interfaces can accommodate them. Thus, the normal process by which managers and engineers accumulate knowledge about products advances modularization by learning how to manage the

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impact of interdependencies, whether or not that learning advances modularity-as-property.

'Modularization as process' also highlights the role of the 'architect' who sets the design rules that mark module boundaries and establish interface requirements. Baldwin and Clark (2000) emphasize that, depending on the interests or objectives pursued by the architect, different module boundaries may be chosen; they differentiate 'modularity-in-production' (MIP) from 'modularity-in-design' (MID) and 'modularity-in-use' (MIU). A given modular boundary and interface specification may achieve both MID and MIP; but often, these two objectives will point toward different boundaries/specifications, presenting trade-offs and requiring prioritization (see Fourcade and Midler, 2004, for an example of a mismatch between MID and MIP that caused a product's failure.) These conflicts are exacerbated if there is not a unitary architect but rather multiple individuals, departments, or organizations determining design rules. Sako and Murray (1999) discuss MID, MIP, and MIU as the focus of optimization, respectively, for product development, manufacturing, and end users. According to Fixson (2006), designers often emphasize low functional interaction, producers easy installation, and users easy disconnection. Thus, modules may not be optimizing modularity-as-property as a unitary technical characteristic, but rather satisficing based on trade-offs among these desired optima or negotiations among various interests.

The relationship between modularity-as-property and modularization-as-process and the influence of a 'modularity' frame

Evolutionary perspectives on product and organizational architectures highlight the crucial interrelationship between modularity as technical property and modularization as learning process. Products are often highly integral when first introduced, as early designs work through a set of complicated issues via coordination-intensive solutions to unanticipated problems (Siggelkow, 2002); at this stage, integral products can often command a price premium based on idiosyncratic features providing new and unique functionality (Klepper, 1996). As experience with designing and building those products accumulates at the focal firm (modularization-as-process), interdependencies across components can be better understood and minimized or anticipated in interface design (Adner and Levinthal, 2001), advancing modularity-as-property. Eventually, a dominant design emerges, allowing standardization and scale (Utterback, 1996) which, in turn, reduces costs, channels innovation efforts, and facilitates the division of labor with specialized suppliers; then, as interfaces are more fully specified, suppliers can develop modules more independently. Thus, over time, industries often follow a trajectory from initial integrality to high levels of modularity in product designs (Sanchez and Mahoney, 1996).

But product architecture need not evolve inevitably toward modularity. Technological change or customer demands for new functionality can redefine module boundaries, may increase interdependencies across modules, and can reverse maturation processes that lead to dominant designs (Abernathy, Clark, and Kantrow, 1984). Thereby modularization processes can cause product designs to swing from modularity toward integrality—and back again (Fine and Whitney, 1996). Undertaken strategically, as a means to improve product performance, this reversal of direction can greatly advantage the architectural innovator; witness Shimano's rise to dominance of the bicycle industry following its innovation of the indexing method of shifting gears (Fixson and Park, 2008).

Modularization understood as evolutionary process is also central to the literature on industry architecture (Jacobides and Winter, 2005; Jacobides and Billinger, 2006; Jacobides, Knudsen, and Augier, 2006). As firms make choices about vertical scope, they are choosing what activities to manage as integral, via nonroutine coordination of critical interdependencies, versus modular, via standardized coordination and independent innovation. Capabilities both inform and follow from these decisions. Firms are more likely to retain activities internally for which they possess superior capabilities, but they may also decide to outsource an activity due to success in mastering interdependencies and specifying interfaces. Subsequently, the firm will strengthen capabilities for retained activities and weaken or lose capabilities for outsourced activities, thereby reinforcing, or changing, the industry's architecture.

The 'mirroring hypothesis' posits a particular relationship between modularity-as-property and modularization-as-process, emphasizing how technical characteristics of a product create a pull toward matched organizational characteristics. From this perspective, a module boundary's 'thin crossing point' vis-à-vis technical interdependencies also

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provides the logical opportunity for organizational disaggregation, i.e., so that design task responsibilities can be allocated to suppliers with specialized expertise (Hoetker, 2006; Cabigiosu and Camuffo, 2011). Examples of mirroring include vertical integration for design and production of crucially interdependent modules versus outsourcing for more peripheral, easily separable modules (for a literature review, see Colfer and Baldwin, 2010).

The direction of causality in the mirroring of different types of architecture is debated. The most common view is that product architecture exerts a powerful force for isomorphism in organizational architectures. But the reverse causality can also be modeled, e.g., when tasks/activities are reallocated across organizational boundaries and patterns of communication/interaction among people involved in product design can change, with the ultimate potential to change the product architecture.

While the mirroring hypothesis anticipates isomorphism in product and organizational architecture, misalignment is not only possible, but may be a strategic choice. Task and knowledge boundaries will not always coincide (Takeishi, 2001). Firms that have historically integrated the components of a complex product risk a competency trap if, from outsourcing, they lose their systems integration capability (Zirpoli and Becker, 2011). Thus, firms that no longer produce certain components may still need to retain the knowledge of how to make them; in the words of Brusoni *et al*. (2001), such firms need to 'know more than they make.' Indeed, given risks of imitation from modularity (Pil and Cohen, 2006), firms may benefit from preserving the interdependencies of a near decomposable product design—even when more decomposition is possible—to maintain the tacit knowledge associated with managing those interdependencies (Ethiraj and Levinthal, 2004).

'Modularity' also provides a cognitive frame for managers and engineers that drives a particular dynamic, and directionality, to the interplay of modularity-as-property and modularization-as-process. A cognitive frame simplifies information processing (Gavetti and Levinthal, 2000) and provides a stable basis for understanding environmental changes (Bingham and Kahl, forthcoming); it affects attention, influencing both automatic and intentional information processing (Ocasio, 2011); it provides a means of interpreting something that is completely new (Tripsas and Gavetti, 2000); it supplies metaphors, symbols, and cognitive cues, 'accenting and highlighting some issues, events, or beliefs as being more salient than others' and suggesting possible ways to respond to them (Benford and Snow, 2000: 623); and it is used by organizational actors to give meaning and legitimacy to their actions (Feldman and Orlikowski, 2011). When strategies are taking shape or changing, internal debates often take the form of framing contests (Kaplan, 2008) in which proponents of different positions seek to make their individual frame into a collective frame through influence activities. Thus, the concept of modularity can provide a powerful cognitive frame for managers rethinking which activities the focal firm should conduct internally and which can usefully be allocated outside the firm to a specialized supplier, and advocating accordingly.

The cognitive frame of 'modularity' will reflect the goals of the senior leader, or dominant coalition, but will be subject to contestation from interests that have different goals or priorities. Furthermore, either modularity-as-property or modularization-as-process can provide the primary or initial orientation for the frame, with an implied sequence and goal.

Summary

I have argued that modularity-as-property is distinct from modularization-as-process. The latter is ubiquitous, linked to ongoing learning about how best to manage interdependencies across and within modules. Modularization processes can, either deliberately or unintentionally, however, lead to greater modularity-as-property or to greater integrality, and this can be true for either product or organizational architecture. The cognitive frame of 'modularity' helps shape the inter-relationship and dynamics of change between these two aspects. Next, I describe the data that informs my analysis of how the three aspects of modularity interacted in the global automotive industry.

RESEARCH METHODOLOGY AND SAMPLING APPROACH

The industry context and case study data I will present were gathered under auspices of the International Motor Vehicle Program (IMVP) through a multi-year project exploring modularity and outsourcing trends at automakers and suppliers worldwide. This project provoked the collective curiosity of a globally distributed team of researchers in the

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IMVP network (named in the acknowledgements and cited as appropriate throughout) who wanted to understand more about modularity, which was then frequently discussed as a factor in the rapid growth, technological innovation, and competitive volatility of the computer industry. Earlier research on product architecture (e.g., Ulrich, 1995) already identified the automobile as relatively 'integral' in contrast with modular products such as bicycles and personal computers. While we did not have a precise way to characterize the two industries in relation to all other industries, we could assert with confidence that they were separated widely apart along a spectrum between modular and integral endpoints.

Thus, these industries could serve as 'critical cases' or 'polar types' (Eisenhardt and Graebner, 2007), with theoretical sampling allowing predictions about the applicability and diffusion of modularity (Yin, 1994). Automobiles are exemplars of complex products that can be analyzed at many different levels, from basic parts and components to subassemblies and functional systems. The auto industry is also global in scope, with multinational firms competing in multiple markets and managing elaborate supply chains spanning developed and developing countries; its outsourcing decisions involve choices among geographically diverse locations and, hence, cast a light on the relationship between modularity and decisions on whether production and design activities need to be proximate or can be globally dispersed.

At the time the data were collected, the computer industry was covered far more extensively in writings about modularity than any other industry (e.g., Langlois and Robertson, 1992; Garud and Kumaraswamy, 1995; Sanchez and Mahoney, 1996; Baldwin and Clark, 2000). By giving the automotive industry an equivalent in-depth investigation, we hoped to challenge facile assumptions that all industries are destined to evolve toward modularity or that modular product architecture would inevitably lead to modular organizational and industry architectures. By examining modularity initiatives over time, we sought to uncover the longitudinal, evolutionary dynamics among different aspects of modularity—our focus was on property and process—rather than inferring causality from cross-sectional data. (My emphasis here on 'modularity-as-frame' emerged only later.)

The advantage of studying a single industry context with multiple firm-level case studies was the ability to hold constant factors that are common for the industry while highlighting factors varying at a regional or firm level. Furthermore, we could see that modularity initiatives varied with respect to firm strategy. Thus, we specifically chose to study modularity initiatives at firms that had certain similarities (e.g., a common starting point of production-based module definitions, a common strategic goal of linking the outsourcing of large and complex subassemblies to the pursuit of modularity), but differed in the extent to which the firms were able to sustain their modularization initiatives over time and accomplish design as well as production gains. Thus, we could triangulate among the common industry context, the common features of the modularity initiatives, regional differences affecting policies on outsourcing, and firm-level differences in outsourcing and modularity strategy to gain analytical leverage.

The global research team undertook several different subprojects, collecting questionnaire data in Europe and Japan and doing interview-based case studies in the U.S., Europe, Latin America, and Asia. For the case studies, two or more researchers were, most often, present at each interview. Extensive field notes were taken; at the request of the respondents, no recording of interviews was done. Interviews were often augmented by plant visits to see module production or by viewings of module prototype designs. Researchers also wrote up and exchanged field notes. Quotes were recorded as close to verbatim as possible; identities of individual respondents have been disguised.

MODULARITY INITIATIVES IN THE GLOBAL AUTOMOTIVE INDUSTRY

Idiosyncratic definition of an automotive module—historical account

The automobile is a complex product, made up of many components and many technologies; as such, it is impossible to characterize as 'modular' or 'integral' in its entirety. Auto industry managers and engineers began to pay attention to modular concepts in the early 1990s, following an earlier logic of unbundling production activities to be carried out by suppliers. The industry's definition of a 'module'—a large chunk of physically adjacent components produced as a subassembly by a supplier and then installed in a single step in an automaker's (known as original equipment manufacturer, or OEM)

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assembly plant—was idiosyncratic from the start; examples are the instrument panel; the front end; seats; and the rolling chassis. By the late 1990s, 'modularity' had drawn the attention of senior executives and was supported by a much broader strategic and financial rationale. The benefits of modular design were now sought, but still within the earlier production-based definition. Here I describe the emergence of this definition and its consequences, drawing on the IMVP longitudinal research project.

Separation of subassemblies

Beginning in the 1970s, the first step in separating tasks to achieve more modular production was to move work off the assembly line to subassembly lines in the same plant. Instead of working awkwardly inside the vehicle body, each task could occur without obstruction on a physically separate, optimized subassembly line, where subassemblies could also be tested before being installed into the vehicle. The benefits were in greater flexibility, improved ergonomics, and better quality; labor cost savings were minimal since employees on the subassembly line typically received the same wages as those on the assembly line.

Seats—the first outsourced 'module'

Starting in the 1980s, U.S. OEMs began to ask suppliers to produce these same subassemblies, leveraging the lower wages at (often nonunion) supplier plants. Seats were the first subassembly to be outsourced. Making seats is a mix of labor intensive operations (sewing covers for seat cushions and stuffing them with foam) and capital intensive operations (e.g., frame construction, electronic seat controls). Seats are physically bulky with a high unit cost, plus variable content due to customer-chosen options, so it is not practical to hold a large inventory. OEMs awarded contracts for entire seats to a single supplier, requiring them to establish dedicated plants within a 30- to 60-minute delivery range and to produce seats just-in-time for a specific vehicle, delivered in exact match to the OEM's assembly sequence. Seats were, thus, the first module (though this name wasn't used until later), carried out by suppliers such as Johnson Controls Inc. (JCI), Lear, and Magna. This approach soon spread to Europe, Japan, and Korea, and by the mid-1990s, no OEMs were still making seats.

More modules defined and outsourced

By the early 1990s, OEMs extended this approach to other subassemblies, still oriented toward production of large 'chunks' of physically proximate components, e.g., the instrument panel—that had previously been produced in their assembly plants. New modules were defined, following the logic of combining bulky or heavy parts, e.g., the front-end module, which includes the front bumper and a front carrier section holding the radiator, cooling fan, and air conditioner condenser, as well as headlamps, airbag sensors, and associated wire harnesses. Not all such modules were transferred to suppliers; doors continued to be built in assembly plants due to the necessary coordination with the paint process.

'Modular factory' as a new organizational concept

In the early 1990s, GM purchasing head Ignacio Lopez de Arriortua declared his goal of building a 'modular factory' to achieve assembly plant productivity of less than 10 hours per vehicle, surpassing the world benchmark. Lopez abruptly left GM for Volkswagen in 1993 to implement this strategic vision. VW's first experiment was at a greenfield bus/truck plant in Resende, Brazil. Resende's 'modular consortium' brought together key suppliers at the common site, under a single roof. VW retained ownership of all assets — land, buildings, machinery and equipment, inventories —so the outsourcing of tasks was not accompanied by an outsourcing of assets (Sako, 2009). Supplier employees built each module within the Resende plant and installed it on the final assembly line. VW purchased the module at the moment of installation; otherwise its role at the site was system integrator, quality inspector, and administrator of human resource policies for all employees at the site (Lung *et al*., 1999). Subsequent notable experiments in Brazil included a greenfield GM assembly plant at Gravatai (named 'Blue Macao,' after birds that mate for life) and a greenfield Ford plant at Camacari, in the Amazon; at both, suppliers were co-located and built large subassemblies for in-sequence delivery. Brazil attracted these initiatives because of government subsidies for co-location, suppliers willing to build dedicated facilities tied to a single OEM, and flexible labor arrangements.

Global extensions: the 'supplier park' concept

The concept of 'supplier park,' like that of 'modular consortium,' refers to the co-location of suppliers in

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close proximity to an OEM assembly plant. Soon after Resende opened in Brazil, supplier parks began to spread throughout Europe. OEMs found supplier proximity an appealing way to implement lean production concepts of minimal inventory. Here OEMs were often retrofitting existing assembly plants to build new models and were able to attract government subsidies for consolidating automotive jobs at a supplier park. (The Mercedes-Benz assembly plant built in Hambach, France, to manufacture the Smart mini car is a greenfield exception.) Suppliers owned their factories and equipment and leased land from the OEM or from the government. A strategic move toward modularity was another stated rationale for these initiatives (Sako, 2003).

Deverticalization intensifies

By the late 1990s, based on their experiences with outsourcing of large subassemblies, automotive OEMs increasingly used the idea of modularity as a rationale to move away from vertical integration for components. This was not a new trend—the U.S. industry reached its peak of vertical integration in the mid-1950s and has declined ever since, and the Japanese industry was never highly vertically integrated. But deverticalization accelerated during this period based on arguments that it was necessary to support 'modularity.' Ideas of 'core competence' were gaining influence in OEM strategy offices around the world. From this perspective, an OEM should not try to maintain excellence in making all components when it could rely instead on the specialized competence of 'best in class' suppliers. This facilitated adoption of the production definition of 'module.'

Outsourcing of design

Once this idea took hold for production, it was a short step to thinking about outsourcing design responsibilities. Japanese automakers already worked closely with their Japanese suppliers on design tasks, although not in explicit pursuit of modularity-as-property. U.S. and European OEMs now also sought the allocation of design tasks to suppliers, under the frame of 'module design,' to tap their specialized knowledge. Suppliers welcomed these overtures (and sometimes initiated them), seeing modules as a means to take on higher value-added activities (Whitford and Zirpoli, 2012).

Thus, increasingly, the auto industry interest in modules went beyond the idea of outsourcing production to suppliers to more ambitious notions of a new division of labor and new methods of coordination. Executives and engineers were stimulated by the powerful example of the computer and electronics industries, where modular design provided powerful combined benefits of cost reduction and speedy, independent innovation (Sturgeon, 2002; Berger, 2006). Automotive OEMs envisioned a world in which they could turn to suppliers for innovative design advances in modules while reducing their own in-house product development staff; where coordination complexity was reduced by the standardization of module specifications and interfaces; where responsibilities for capital investment, quality verification, logistics, and product liability could be shifted to suppliers; and where they could reduce their heavy load of assets and become more agile, nimble companies with improved ROAs (Sako and Warburton, 2002).

These ambitions first had to face the reality that automotive modules are defined within a closed (i.e., proprietary to a given firm and its suppliers) rather than an open (i.e., industry-level standards) architecture (Takeishi and Fujimoto, 2001; Garud and Kumaraswamy,1995). Open modular architecture makes it possible for any capable supplier to build a given module, while closed modular product architecture needs to be supported either by a fully vertically integrated firm or by 'black box' subcontracting, where the customer provides proprietary specifications to a chosen supplier.

Creation of megasuppliers

As OEMs sought to outsource more modules to suppliers, moving beyond seats, they found few suppliers capable of taking on the full set of design and production responsibilities. Industry analysts and investors predicted a necessary consolidation to create suppliers capable of handling this incipient demand. The pace of deverticalization increased dramatically at U.S. OEMs when first GM and then Ford spun off their captive parts divisions, creating Delphi in 1998 and Visteon in 1999, respectively, as the first 'megasuppliers.' More megasuppliers were soon formed from horizontal merger and acquisitions of existing automotive suppliers to compete for module contracts; these firms were expected to take over critical design and engineering tasks, to handle more complex manufacturing and logistics tasks, and to assume a larger role in the management of second- and third-tier suppliers. European

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megasuppliers included Faurecia, Valeo, and Sommer Allibert in France and Bosch and Siemens in Germany; North American megasuppliers included Johnson Controls, Lear, and Magna.

Analysts greeted these developments with further predictions of computer industry-like dynamics. A Bain and Company report (Donovan, 1999: 6) wrote about 'the dawn of the megasupplier,' predicting that they would quickly 'design vehicle systems that can be standardized within and across OEMs—in other words, used in multiple models of an OEM and eventually by multiple OEMs.' Fine (1999: 62) predicted that Chrysler, in taking the lead in outsourcing design work to megasuppliers, would be:

> '. . . the Compaq of the auto industry. Just as Compaq helped to drive the entire computer industry to a horizontal/modular structure, Chrysler's strategy allows suppliers—even Ford's and GM's suppliers—to strengthen their capability to develop whole automotive subsystems, thereby pushing the entire structure of the industry from vertical toward horizontal.'

Regional variation in modularity emphasis

Beyond Brazil and Europe, the emphasis on modularity in other regions varied widely. GM had plans to bring the 'Blue Macao' concept from Brazil to the U.S., under the code name 'Project Yellowstone.' The United Auto Workers opposed the plan as a ploy to increase outsourcing to nonunion suppliers, so GM backed away from Project Yellowstone *per se*, but nevertheless continued to outsource aggressively. For example, it moved responsibility for full interiors to Magna and the GM engineers supporting interiors became Magna employees. Ford, building on its experience in Europe, was the first to introduce a supplier park in the U.S. during the retrofitting of its Chicago assembly plant. Chrysler, historically less vertically integrated than GM and Ford, was the first of the Big Three to outsource both design and production to suppliers. Overall in the U.S., the pursuit of modular production provided the rationale for accelerating outsourcing already underway at the component level. Ford's modularity initiative is covered later.

In Japan, Toyota and Honda showed little interest in modules, believing they were already gaining the benefits of design and production collaboration with their suppliers without any shift in product architecture, and that the pursuit of modules could lead to quality problems. These companies did, however, create more subassembly lines within their assembly plants, following a modularization process of separating once-bundled activities (Takeishi and Fujimoto, 2001). Nissan, during its 1999 to 2001 'revival plan,' restructured its relationship with keiretsu suppliers substantially, selling equity stakes and redefining contract terms. One newly independent supplier, Calsonic Kansei, started doing module assembly inside Nissan assembly plants, a version of the modular consortium.

In Korea, dramatic restructuring in the late 1990s brought Hyundai's acquisition of Kia; their vertically integrated suppliers came together as Hyundai Mobis, which was then spun off. As Hyundai set out to improve its brand image and quality reputation, its manufacturing strategy revolved around an extensive use of modules produced by Mobis; this case will be covered in more detail later.

Analysis

The historical account (summarized in Table 1) shows that the concept of 'modularity' was not initially evoked when the movement of production tasks off the main assembly line began. The initial frame was closer to a 'focused factory' idea (Skinner, 1974) in which specialized lines would be matched with specialized products. The frame of outsourcing was next, as OEMs sought to lower their labor costs and, at this point, the idiosyncratic production-based definition of an automotive 'module' became well established. This definition then affected subsequent attempts to pursue design gains that became the heart of the strategic rationale for 'modularity' at both OEMs and megasuppliers. Knowing that modules were already defined and in production before the frame of 'modularity' swept through the auto industry is essential to interpreting the subsequent dynamics of modularity initiatives.

Also crucial is a grounded understanding of exactly how a 'module' is defined differently in the auto industry than in the information technology world (Sako, 2003). As noted earlier, automotive usage defines a 'module' as a chunk of physically proximate components that are subassembled independently from the rest of the vehicle, tested for functionality, and installed in a single step in final assembly. Taken strictly on these production-based terms, modularity did increase in the automotive industry in the 1990s.

However, these automotive modules clearly violate the Ulrich definition. More than one function

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Table 1. Emergent production-based definition of automotive modules

Event/activity	Timeframe	Goals/advantages	Consequences for module definition
Separate production (moving work from main assembly line to subassembly lines in same plant), still vertically integrated	Beginning in 1970s	Subassembly tasks physically easier to do, ergonomically better, logistics more efficient; quality testing done before installation; labor flexibility. Frees up space, reduces complexity on main assembly line.	Logic of which subassemblies become 'modules' becomes clear. What is moved to subassembly line is 'chunk' of large, heavy, bulky, physically proximate components, for which production advantages of separation are greatest. First done for seats.
Separate production, outsourced to proximate suppliers	Begins in late 1980s	Take advantage of lower (often nonunion) supplier labor; supplier has delivery and quality responsibility.	'Chunks' begin to be called 'modules.' Emphasis on supplier being able to produce and deliver in time for in-sequence production. Module boundary/ interface designed for one-step installation at assembly plant.
Experiments with 'modular factory'	Early to mid-1990s	On-site suppliers coordinate closely with OEM and each other; take on more responsibility for quality, logistics.	'Module' is now central concept for this production experiment. More production-defined modules established; e.g., front end, instrument panel, and chassis, as well as seats.
Diffusion of supplier parks	Mid- to late 1990s	OEMs improve logistical efficiency. Supplier proximity supports in-sequence assembly. OEM keeps integrator role.	Production-based division of labor becomes well established. Suppliers develop mastery in production of modules, begin to seek design role.
Deverticalization by OEMs intensifies	Late 1990s	OEMs seek more agility, ability to access new suppliers, increase in competitiveness of spun-off parts divisions.	Spin-off of Delphi (from GM); Visteon (Ford); Mobis (Hyundai) changes relationship with parent OEMs; spin-offs seek more independence, more autonomy, bigger role in designing modules.
Creation of megasuppliers	Late 1990s to early 2000s	Pursuit of scale; amassing capabilities to support OEM globalization, take on higher value-added production and design tasks vis-à-vis modules.	Megasuppliers created around strategy of building modules, based on production definition that brings together components from many functional subsystems. Rationale is to horizontally combine the expertise needed to build and design those modules. Design gains difficult to achieve, knowledge doesn't encompass all functions included in a module.

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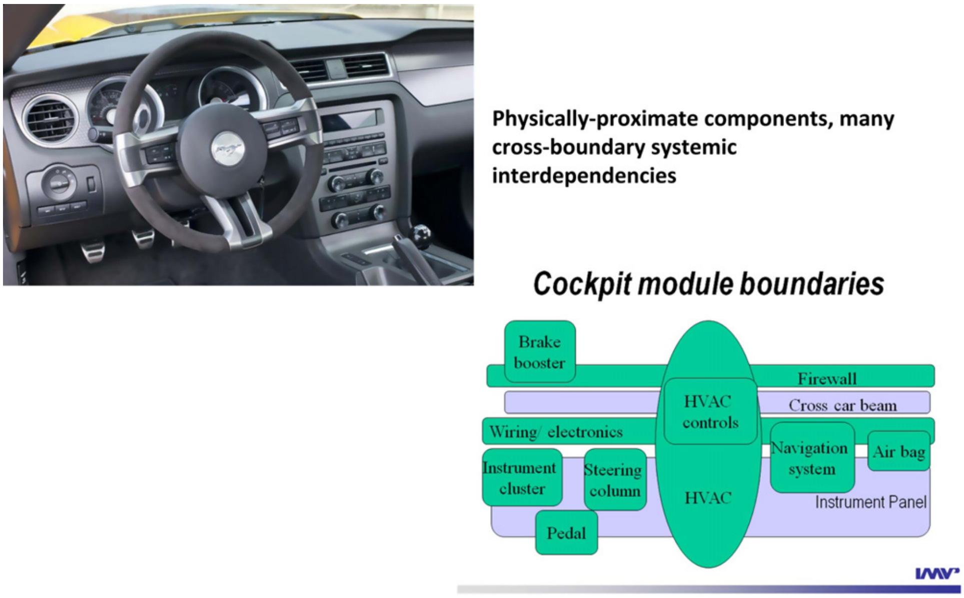

Figure 1. Instrument panel (cockpit) as 'module'

is mapped to the chunk; Ulrich would take this 'many-to-one' characteristic as evidence of integrality. Furthermore, automotive modules, like the overall product, have a closed rather than open architecture; designs are OEM specific, with no standardization of modules at the industry level. Indeed, there is no standardization of modules even at the firm level. Module boundaries (including which components are included) typically differ across different models in an OEM's product line (Sako and Warburton, 2002).

The organizational architecture associated with automotive modules was also optimized for production. Production tasks were first disaggregated but kept within firm boundaries, then moved outside the firm to take advantage of lower wages and to draw on (and/or develop) the specialized production expertise of suppliers. Organizing for supplier proximity, either in a 'modular consortium' or a 'supplier park,' was pursued to reduce inventories and improve coordination efficiency. None of these organizational arrangements furthered design improvements in modules.

Indeed, the prioritization of production goals created barriers to making designs more modular. Consider the instrument panel module (see Figure 1). Functional interdependence is high, given the tight intermingling of components that support steering, climate control, entertainment, driver information, and safety. But interdependence is also high across the module boundary, since most of these functions require components elsewhere in the vehicle—e.g., in the body, electrical system, transmission, cooling system—to be operable. A lot of design coordination is required to optimize its fit to a specific vehicle's space constraints, driving characteristics, and market positioning.

Furthermore, emergent phenomena such as NVH (noise, vibration, and harshness), either within or across modules, can be modeled but not fully anticipated or assessed before the final vehicle is complete. In the absence of standardization across firms, or even models, suppliers can't gain advantages of design specialization and scale that would obtain from a fully specified, industry standardized module.

As OEMs defined more modules and sought to outsource their production, their need for more specialized supplier expertise grew. For example, megasupplier Sommer Allibert was created in a merger intended to facilitate one-stop access to specialized expertise in electronics and plastics for outsourced production of instrument panels. Since its expertise did not encompass all the functions contained in an instrument panel, Sommer Allibert was not immediately well positioned to achieve design gains, although it had the potential to amass knowledge over time about interdependencies within and across the instrument panel boundary through modularization processes.

Even with this increase in outsourcing to megasuppliers (the extent of which varied by

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module, see Fixson, Ro, and Liker, 2005), OEMs retained a central role in design engineering, product development coordination, and system integration. Indeed, the difficulties megasuppliers had in pursuing modular designs caused them to engage in intensive coordination with OEMs rather than innovating autonomously as expected under the 'modularity' frame. Modularization-as-process within megasuppliers and in coordination with OEMs did lead (in some, but not all, cases) to slow, incremental increases in design modularity. However, even these modest changes were the *ex post* outcome of integrative organizational processes, rather than an *ex ante* condition that facilitated reduced coordination, consistent with Cabigiosu and Camuffo's (2011) findings in the air conditioning industry.

Overall, the barriers to achieving design modularity, among other factors, prevented the anticipated migration of value from OEMs to suppliers and the predicted shift from vertical to horizontal structure. The computer industry analogy simply did not hold.

Thus, it is no surprise that the ambitious strategic goals of automotive executives for moving toward greater modularity-as-property could only be partially met. Attainable were the goals of moving asset-intensive activities to suppliers; tapping supplier production expertise; reducing manufacturing costs; and reducing complexity on the main assembly line. Other design goals could not be readily attained. Coordination costs during design and procurement were often higher, not lower; standardization of modules at an industry level was not supported by any OEM; and innovation was still constrained by the tight design interdependence among suppliers and with the OEM.

The 'modularity' frame did not help executives understand this misalignment; rather it raised expectations that gains seen in industries with more modular product architectures, e.g., computers, could be attained for the auto industry, too. The resulting frustration was a major contributor to what happened with firm-specific modularity initiatives. We turn now to examine two such initiatives in detail.

Modularity at Ford Motor Company: production definitions that constrain design ambitions

This case study explores the modularity initiative at Ford Motor Company from three perspectives: (1) the corporate-level executives, managers, and staff who mobilized the initiative from the start; (2) a supplier's product development team working on a module design to propose to Ford; and (3) a Ford chief engineer and his team of product development engineers who were making decisions about whether or not to incorporate modules in their current vehicle project. We started data collection with corporate-level interviews in 1999; we continued with supplier interviews in 2000 and Ford product development team interviews in 2001; and we returned to corporate-level respondents, also in 2001, for an update.

Antecedents and initial steps

Ford was one of the first OEMs to implement supplier parks extensively, particularly in Europe. Accordingly, Ford had experience with the production-dominated module definitions and outsourced organizational arrangements with suppliers that manufactured seat, instrument panel, and front-end modules in nearby plants.

Suppliers sought a broader design role at a module (rather than component) level and Ford was not organized to respond to this request, prompting the modularity initiative. An engineer told us:

> 'We have integrated suppliers very well into the component approach to product development. It's hard to tell who's a Ford person and who's a supplier person on the platform teams. But we don't know how to evaluate a module proposal because we're organized around components. It's difficult to figure out if suppliers have all the capabilities we think they need for modules.'

To increase its ability to evaluate module proposals, Ford established a corporate-level modularity task force with cochairs from product development and manufacturing plus representatives from corporate strategy and purchasing. After internal study and external benchmarking, the task force identified 19 modules making up the entire vehicle, using production-based definitions consistent with industry usage at the time; according to task force documents, a module was defined as 'assembly of a significant number of components designed and optimized as a subassembly before installation on the vehicle on the main assembly line' (Ford Motor Company, 1999). Also stated in these documents were goals for the shift to modules: reducing the number of parts; defining interfaces with adjoining components; setting common 'hard points' so a

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module could be positioned correctly for automated sections of the production line; testing functional quality before final assembly; making installation easier; and improving logistics. The 19 modules (called Class 1) were later subdivided into submodules (Class 2 and Class 3), totaling 44 in number. Having submodules, it was believed, would reduce the barrier to adoption of modules by product development teams within Ford; vehicle projects could ease into modularity by adopting some Class 2 and Class 3 submodules and then move up to Class 1 full modules in the next product cycle.

Despite the production-based definition of module boundaries, the ambitions of the modularity initiative were clearly to leverage the benefits of design modularity. The CEO's aim was to restructure the division of labor between the OEM and the supply base. According to an executive on the task force:

> '[The CEO] sees modularity as a way to share capital risk and assets with the supply base, so we don't have to be so big. Plus, modules should get us to the next level of design innovation. We want to design and build a vehicle quicker, better, cheaper, closer to what customers want. If we do modules right, it will change how we think about building the vehicle. It will put the expertise in the supply base, where it should be.'

Ford executives had seen these design-derived benefits enacted in the computer industry and wanted to reach beyond the already underway outsourcing of production for the small number of well-established modules. By defining the entire vehicle in terms of 19 modules, the task force presented Ford's organization with multiple challenges. First, Ford had not been granting design responsibilities to suppliers on a modular level of aggregation; supplier involvement with product development had been taking place within Ford's product development teams, often with co-location and at a component level. Second, many of the 19 modules were still manufactured entirely within Ford, so now the issue arose of whether suppliers were capable of manufacturing them efficiently.

Ford proponents of modularity cited both technological and organizational advantages of giving design responsibility to suppliers. Some focused on the prospects for more innovation, plus cost savings, from outsourcing design to suppliers. According to one engineer, 'We should simply give suppliers a target price and say 'you figure out how to make it.' If we keep doing all the engineering, we don't save anything.' Other managers emphasized accountability and the reduced coordination requirements from assigning an entire module, e.g., seats, to a single supplier, as opposed to the past practice of dealing with many suppliers providing their respective parts to Ford's seat manufacturing line at the assembly plant.

Yet many Ford engineers saw risks to product performance and brand identity in outsourcing too much to suppliers. One engineer said, 'We've got to be clear on what makes a Ford a Ford. We can't give away control of those things.' Another engineer agreed: 'Most modules affect look and feel.'

At the same time, there was recognition that Ford's capability for module design was limited and needed development. A product development manager said, 'Our first intention has been to design in-house a generic module design and then give it to capable suppliers. But we haven't been so good about designing for modularity. Our engineers have a component mentality.'

Ford's managers were aware that the shift to modules would put many new demands on suppliers, beyond the issue of their design capabilities. According to one manager, 'We need to certify that a supplier is module ready. They will need lots of project management skills. We expect them to manage Tier 2 suppliers. We will want them to test modules the same way we would.'

For those focused on outsourcing the manufacturing of more modules to suppliers, a different set of concerns—about cost—arose. As one product engineer explained, 'It may not work to take our design and build it somewhere else. There could be a very good rationale for keeping it inside.' According to one engineer, 'We're not really optimizing the design of a module—often we're just seeing a subassembly that we used to build now being pushed out to a supplier. The freight costs can be very high unless the supplier locates nearby.' Many felt that design gains, not manufacturing savings, were the key to modularity being a success: 'Most modules we've checked out are cost plus; it costs the supplier more to make than for us to do it. We need more design improvements from suppliers to justify doing modules.'

From these differing viewpoints, either Ford or its suppliers could be the preferred location for either design or manufacturing, with the net benefit dependent on how successfully each mastered its assigned tasks. While each interview subject expressed his/her own preference for task allocation (e.g., design

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by Ford, design by supplier), it seemed likely that choices, at least at this initial stage, would be contingent, varying by which newly defined module was under consideration.

Yet the corporate imperative behind the modularity initiative was more absolutist. According to one executive, 'I don't see anything that we're not willing to outsource. We should focus on system engineering and common standards.' This message encouraged the ambitions of Ford's suppliers, who were eager to take on full responsibility for module design.

Visteon develops a new modular design

Our interviews in 2000 focused on Visteon (the first tier supplier that spun-off from Ford) and, as a specific example, its modular design for a super-integrated instrument panel, known as SI-IP. Visteon's strategy was to emphasize its capability to be the system integrator. As the chief engineer for SI-IP told us, 'We always did the full integration for Ford in the past *[when vertically integrated]*, so we fully have that capability. Most electrical suppliers don't have that breadth.' Another SI-IP engineer expressed his ambition to 'break down barriers between the modular design approach in electronics and the more integrated design approach in autos.' Visteon invested heavily in advanced technology for the SI-IP, filing 100 patents and 500 disclosures.

The traditional IP is built around a beam of steel that bolts across the back of the engine compartment. Plastic moldings, which provide the IP's shape and surface texture and define cavities for components and storage (i.e., glove box), are then attached. Various components are then assembled into the structure, including instrument cluster (speedometer, gauges), HVAC controls (heating, ventilation, air conditioning), audio system, and at times, steering column and brake pedal. A traditional instrument panel is a tangled mass of clunky metal boxes weighing 80 to 100 pounds. The bulk and weight were consequences of component-based design. Each component had its own protective housing, heat sink, and microprocessor. With many separate components, assembling the IP involved many electrical connections, each a potential source of quality defects and ergonomic problems for assembly workers.

Visteon's SI-IP design aimed to move away from this component-based approach. Using a single casing, with structural metal embedded in the plastic molding, reduced size and weight substantially. Integrating the housing for a fan motor into this casing allowed for a smaller and lighter motor. Electrical functions were consolidated onto a small number of integrated circuit boards. The module was designed with a hinge along the back edge, allowing the top half of the IP to open up to facilitate replacement of boards and installation of software. Based on consumer electronics designs, engineers chose a single motherboard designed for longtime functionality and put electrical functions that might be upgraded more frequently on separate boards. In place of wire harnesses with bulky connectors, SI designers used a flat wire technology that allowed highly flexible positioning of components and eliminated heat sinks.

The gains claimed by Visteon for the SI-IP design were impressive—a 44 percent reduction in weight, a 30 percent reduction in the number of components, a 20 percent reduction in cost, a 10 percent reduction in NVH (noise, vibration, harshness), and a 30 percent reduction in quality defects, plus much lower cubic feet requirements for the overall physical package. At the same time, Visteon engineers were aware of technical challenges facing SI-IP, given an automobile's demanding operating requirements: 10+ year durability, high reliability in extreme temperatures, holding up under constant vibration, and resistance to oxidation, corrosion, and water. But they were optimistic that their design would stand up to Ford's rigorous testing.

However, they worried about organizational arrangements with Ford. First, Ford was losing the potential cost benefits of having Visteon do the module design by insisting on having its own engineers monitor—through 'shadow engineering'—Visteon's work, as the SI-IP chief engineer explained:

> 'OEM engineers are monitoring engineers at suppliers who are fully capable of doing the job. Each one is afraid of having something bad happen on his watch . . . So the cost benefits of modules aren't being realized.'

Second, they saw how Ford's purchasing organization— in structure, routines, and incentives vis-à-vis risk tolerance—was not well suited to evaluating a module design proposal from a supplier:

> 'When they have to evaluate something like this, their organization begins shaking. Purchasing wants us to break everything down to the subcomponent level so they can call in their technical experts to check out the costs. Then either they can't quite assess the technical characteristics of the integrated

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design, which makes them nervous, or they see that it's great, which is threatening . . . Ultimately, even if they like the design and improvements we offer, they don't want to take the risk of the whole package.'

Ford's reaction to Visteon's modular design

In 2001, we spoke with the development team for a product being redesigned for the 2005 model year about how they thought about utilizing Ford's defined modules. The Ford project team had evaluated the super-integrated instrument panel design we had studied at Visteon. As the engineer involved in that evaluation explained:

> 'The SI-IP from Visteon was a great concept. We would have gotten a huge glove box— it would have sold the car. I was willing to take a $5 to $10 penalty on it. But it didn't work. The ribbon wiring didn't meet our temperature or vibration requirements. The IC cards installed on their edge also had a big vibration problem—laptop computers don't use them for that reason. The idea of opening the instrument panel to put in new cards for programming or new functionality was great, but with the windshield there, how could you do it? And even though SI-IP passed the initial tests, it failed all the extreme condition tests.'

This engineer acknowledged that the SI-IP, as a new modular design, faced an uphill battle amid the tight time lines, quality tests, and cost targets of a typical product development project:

> 'Even if SI-IP had passed all the tests, you would worry a lot. You'd throw double engineers on it, really harass the suppliers to make sure everything is working. It would cost a lot, you might get a pat on the back, or you might not.'

The chief engineer described other examples of why his team judged various modules to be unworkable. With the 'door inner' module, Ford's purchasing assessment concluded that there was no available supplier with all the capabilities needed to design and build the entire module. Furthermore, its heavy weight would mean having a supplier build a partial module with remaining manufacturing steps done on Ford's assembly line. The team judged the cost of this mixed approach to be too high.

The project team also considered using a front-end module (FEM). This would reduce weight by 20 pounds, and quality would improve from installing the FEM straight into the open end. But the current assembly plant layout didn't allow for installing the FEM in one step. This time, the project manager decided, it would be better to build the front end from components, pending the plant's retrofit.

While component-oriented purchasing routines and factors driving up manufacturing cost were major barriers, knowledge-related issues were a greater challenge, according to one engineer:

> 'We know how to design a component (and how to tell a supplier to design a component), but I'm not sure we have the systems engineering capabilities to design a module. When you're designing a whole set of components brought together in a module, you need to understand every interface deeply.'

All in all, the chief engineer described a striking reversal in their thinking during the project:

> 'Our goal was to use all 19 modules . . . But in the end, after many false starts, we didn't use a single module.'

His ultimate conclusion was that:

> 'There's no point in modularity for its own sake. It's like Don Quixote pursuing the impossible dream. I can see why suppliers want to do it. It brings more value-added into their plants. But despite my best intentions, I simply couldn't justify doing it.'

Analysis

The Ford modularity initiative demonstrates how differently groups within an organization can frame 'modularity' and the consequences for both modularity-as-property and modularization-as-process. Tensions rose due to conflicts among the production-oriented definition adopted by the modularity task force, the design-oriented ambitions of senior executives, and the skepticism of engineers about whether suppliers had the capabilities to meet the new strategic vision.

As noted in the earlier historical account, the emergent production-based industry-wide definition of module arose before the term 'modularity' had become common currency, at Ford or at any automaker. Ford's pursuit of modularity-as-property was heavily influenced by path dependence in how modules came to be defined at the industry level as chunks of physically proximate components. The external pressure from Ford's suppliers, seeking the opportunity to bid on a full module rather than components, also affected the task force's definitional choices and subsequent activities.

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The action by the modularity task force to define the entire vehicle in terms of 19 Class 1 modules led almost inevitably to a full set of production-based definitions, given that certain modules were already well established on that basis throughout the industry. These definitions also conveyed an idea of fixity about module boundaries that was perhaps inappropriately rigid at the early stage of a modularization process. This confirms that the task force saw its task as achieving modularity-as-property and gave little explicit attention to modularization-as-process; this then corresponded with production-oriented module definitions that paid little attention to the potential for design gains.

Yet despite this orientation, ambitious goals related to module design were being set from the start. Senior executives were particularly likely to apply the analogy of the computer industry in pursuing a strategy of modular design innovations generated by specialized suppliers. The CEO's strategic intent for modularity was to change the boundary of the firm, allocating more tasks, more investment requirements, and more risk to suppliers—essentially the 'modularity' frame as enacted in the computer industry and projected onto the auto industry. Particularly appealing was the idea of being able to set a target price and then turn everything over to a capable and accountable supplier; this set up an expectation that suppliers would work autonomously on modules, achieving lower costs and faster, better innovation.

Ford managers and corporate staff tended to accept this framing as legitimate and warranted, cognitively adjusting to how this new strategy differed from the past. For example, whereas the earlier cognitive frame of 'core competence' had originally meant retaining control of such key components as engines, the overlay of the 'modularity' frame no longer required such choices. Ford was already outsourcing engines and, in the words of one manager, 'I don't see anything we're not willing to outsource,' provided that Ford focused on 'system engineering and common standards.'

In contrast, Ford's engineers tended to be more focused on the pros and cons of achieving modularity-as-property. The perceived advantages included assigning full responsibility for cost, quality, and delivery to a single supplier, thus reducing coordination requirements, simplifying procurement, and improving accountability. Their list of disadvantages was longer: difficulty in assessing supplier module proposals due to knowledge at Ford being organized around components; higher costs because of lesser supplier efficiency; loss of brand differentiation because suppliers would have less commitment or ability to generate the Ford vehicle 'look and feel;' loss of quality and reliability because of lesser project management and testing capabilities at suppliers; and redundancy in engineering effort because of Ford's need to monitor suppliers. Note that most of this list revolves around skepticism of supplier capabilities.

Ultimately, neither senior executives and managers nor engineers explicitly addressed the central dilemma—the not-very-modular-for-design nature of the defined modules, i.e., large interdependencies existing across module boundaries due to functional systems that spanned modules—that made decisions about whether design should stay at Ford or be outsourced so difficult. Their debates, rather than reflecting disagreements about the wisdom of outsourcing (all respondents viewed an increase in outsourcing as necessary and mostly advantageous), were instead addressing fundamental questions about how to set the appropriate knowledge and task boundaries between OEM and supplier, given multifaceted cost, quality, and product performance requirements. Yet discussion of these issues was distorted by lack of recognition of the consequences of the idiosyncratic path to a production-defined module.

When we interviewed Visteon's engineers as they worked on an innovative module design, essentially moving to adopt the new role proffered them by the strategic vision of Ford's CEO, we found they combined the managerial and engineering frames found at Ford. Like Ford's executives, they saw a potentially new division of labor and welcomed the opportunity to be more autonomous, take more design leadership, and achieve higher margins. Yet they shared many of the worries of Ford's engineers, albeit with an understandable difference in perspective; they felt Ford didn't trust their capabilities enough, was too inclined to monitor them, and couldn't break out of its component mentality. Also understandable is their belief that they could handle module design on their own, without much coordination with Ford. Only by making this conviction a reality would they be able to escape from the subsidiary and dependent position that automotive suppliers were accustomed to occupying in the automotive design process.

Ford's pursuit of modularity-as-property significantly affected how both Ford and Visteon

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approached modularization-as-process. Ford defined module boundaries on its own and then engaged in heated internal debate about whether design responsibility for modules should or should not be transferred to suppliers. This decision was often described in either/or, zero-sum terms, i.e., either Ford would transfer responsibility to a supplier or would keep the module in-house. Ultimately, Ford's managers favored supplier autonomy, while Ford's engineers (and purchasing agents) feared it. This debate also reflected the under-the-surface (and perhaps not entirely conscious) divergence in opinion about whether senior management's framing of 'modularity' using the analogy of the computer industry was, in fact, applicable to the auto industry.

Visteon's engineers also approached the modularization process as an autonomous activity, believing they had system integration capabilities superior to other suppliers. Indeed, they found ample opportunity, in their SI-IP design, to achieve reductions in weight and number of components, and they confidently predicted reduced costs, fewer defects, and greater flexibility via software upgrading. They chafed under what they saw as an OEM's outmoded insistence on control (manifested in demands and oversight from Ford), which they felt constrained them from increasing Visteon's share of value-added.

Explicit in this complaint was the idea that Ford should be matching the new technical architecture with a new organizational architecture. Unacknowledged in this anticipation of 'mirroring' was that this new way of organizing would require more integration of expertise, more interaction, and more attention to interdependencies—both intra- and interorganizationally—than in the long-established component approach to design. This created tension given expectations (shared by Ford and its suppliers) about the benefits of lower coordination, reduced cost, increased speed, and more innovative features that would arise from granting capable suppliers autonomous control over module design.

When the chief engineer we interviewed explained his reasons for not accepting any of the module proposals submitted for his current project, his list for most modules was dominated by production-related concerns, e.g., additional automation needed for one-step installation of the door inner; insufficient space for installing the front-end module at the assembly plant. However, his objections to the Visteon instrument panel proposal were based on Ford's assessment that the SI-IP had serious design failings—e.g., not meeting temperature or vibration requirements; not functioning reliably under extreme conditions; not feasible to open the instrument panel to install new IC cards given the windshield angle.

Recall that Visteon engineers criticized any Ford organizational routines that interfered with their ability to move fully into module design. Yet the fact that the Ford chief engineer found so many problems with Visteon's instrument panel prototype hardly suggests that the design would have been improved by more supplier autonomy. Earlier and more frequent interaction between Ford's engineers and Visteon engineers, understood not as excessive monitoring but as a modularization process to increase mutual learning about interdependencies and interfaces, might have resulted in faster and better resolution of problems before the SI-IP design was completed.

Those Ford organizational routines also held back the Ford chief engineer. He worried about choosing a module that would inflate the costs of his current project, even if it paved the way for company-wide implementation in the future. At the same time, he felt putting lots of extra Ford engineers on the task of assessing a supplier's design proposal was the only way to mitigate his personal risk; since this would add cost, a critical metric, he was even less likely to choose a module.

So while the modularization process hypothetically advances steadily toward a better understanding of interdependencies and, hence, more beneficial choices of module boundaries and interfaces, the Ford case reveals how that process can be blocked, interrupted, or misdirected. When expectations of cost reductions and lessened coordination weren't immediately met, the powerful imperatives of completing a vehicle project on time and at budget (which drove the chief engineer's incentives) overrode corporate-level goals of increased adoption of the task force's defined modules.

It seems likely that the overlap of task and knowledge boundaries (however much complexity this added), and even Ford's 'shadow engineering' (despite the risk of redundancy), were necessary to achieve design gains with production-defined modules, certainly during a transition of moving from components to modules as the focal level of analysis. Neither party seemed to recognize this, despite (or perhaps because of) Visteon so recently being a vertically integrated division within Ford.

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Coda: reconsidering modularity strategy

In 2001, we returned to ask members of the original modularity task force about Ford's modular strategy. A senior manufacturing executive emphasized how much time and cost and capability building would be required to make modularity work and acknowledged that Ford had not understood this in implementing the strategy:

> 'Doing this right requires a high level of skills on both sides [OEM and supplier] and we're just coming to grips with that. We at Ford need to be better at the systems engineering than we are. Neither we nor the suppliers really understand how the electronics in an instrument panel module need to interact with the electrical system in the rest of the vehicle. Plus the suppliers need to understand a whole lot more about the customer, the warranty system, our dealers, etc. Right now, the suppliers have less engineering talent than we do, so we're reluctant to pass the design to them. It's easier to go with components and take the "pass the screwdriver" approach . . . We built a great strategy and we've been abysmal about implementing it. It's still the right strategy and it still presents us with huge opportunities. But there are lots of skeptics in the company now because of how we've gone about this.'

The skeptics prevailed when Ford disbanded its modularity task force in 2001 and reduced its efforts to persuade chief engineers to adopt the defined modules and submodules in their vehicle projects. Modules did not disappear by any means; front-end modules and traditional IPs, built up as modules at supplier plants, are visible to this day as one-step installations in a number of Ford assembly plants. But the more ambitious goals for design gains from modularity-as-property went by the wayside.[1]

To the end, the framing of modularity by Ford executives and corporate-level managers and staff remained the same. Their emergent recognition was that Ford's capabilities for system engineering of modules were not all that strong, that supplier capabilities for doing module-level design innovation were also underdeveloped, and that both parties needed to do much more work to understand all of the interfaces. Thus, Ford's framing perceived incomplete achievement of modularity-as-property as a consequence of inadequate capabilities, rather than seeing modularization-as-process as a steep technical learning curve, given high interdependencies across production-defined module boundaries, requiring a patient, long-term commitment to seeing what design innovations might emerge over time. This latter view is better represented in the next case.

Reorganization for modules at Hyundai Motor Company

Hyundai Motor Company is arguably the automaker most heavily engaged in using modules to manage complexity, improve quality, and reduce costs. This contrasts with OEMs like Ford that have backed away from modularity initiatives (even as modularization processes arguably continue there and at all automakers). Hyundai's approach to modularity depends heavily on a unique relationship with its sole-source module supplier, the now-separate megasupplier known as Mobis that was once a vertically integrated division within the huge Hyundai *chaebol* (conglomerate). Together, Hyundai and Mobis evolved to an approach that stays fundamentally oriented toward production advantages from modularity while also making slow but steady progress toward design gains—accomplished within highly integrated organizational arrangements that support an ongoing modularization process.

History of Mobis: its relationship with Hyundai Motor

Established in 1977 to make shipping containers, Hyundai Precision became a contract manufacturer for Hyundai Motor in the 1990s. The financial crisis in Asia in 1997 forced Korean automakers Daewoo and Kia into bankruptcy. Hyundai acquired Kia, and Hyundai Motor was created as a freestanding company in 2000, separate from the rest of the Hyundai *chaebol*. Meanwhile, Hyundai Precision was restructured to include just automotive parts businesses and was renamed 'Mobis' in 2000 after acquiring parts operations from Hyundai and Kia.

[1] The controversy of Firestone/Bridgestone tires and rollover accidents involving the Ford Explorer SUV was unfolding in 2000 and 2001, with the first federal government alert in May 2000, a Firestone recall in August 2000, and a further Ford recall in the spring of 2001 after a severing of the 100+ year relationship between the two firms. As a result, CEO Jac Nasser, who had been the lead champion of the modularity initiative, stepped down from his position in October 2001. Investigators did identify a distinctive interaction between vehicle design and tire design as the most likely cause for the high number of Explorer rollover accidents, bringing home the unusually high level of design interdependencies affecting automobiles. This event, combined with Nasser's departure, undoubtedly affected Ford's inclination to continue its high-level pursuit of modularity-as-property for the entire vehicle.

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Moving toward modularity was an important strategic rationale for the restructuring. The initial product lineup consisted of three core automotive modules—chassis, instrument panel, and front end. Module definitions fit the industry's production-based norm. Hyundai Motor was initially the only customer.

Spinning off Mobis was in keeping with the trend of deverticalization in the auto industry worldwide. But from the point of view of structure and governance, Mobis has certain unusual features. When Mobis was created, the founder and chairman of Hyundai, Chung Mong-koo, insisted that the Hyundai/Kia aftermarket parts business be included so that its high margins could subsidize the new module business; as a result, Mobis' R&D expenditures are higher than virtually all other Korean suppliers. Mobis is also the official holding company of Hyundai Motor, as well as its largest shareholder; plus the CEO and other senior executives at Hyundai Motor worked previously at Mobis. As a result, the financial and managerial relationship between Mobis and Hyundai Motor is much closer than the counterpart examples of Delphi (spun off from GM) and Visteon (spun off from Ford) in the U.S.

Hyundai saw many production advantages in having Mobis as a separate company. While Hyundai Motor's plants are entirely unionized, Mobis is nonunion and often relies on outside agencies to provide temporary or contract employees, allowing substantial wage differentials between Hyundai Motor and Mobis plants in Korea and elsewhere. Mobis plants are deliberately located close enough to Hyundai and Kia assembly plants to provide frequent sequenced delivery of modules and keep inventories low, while also being far enough away to draw on a different labor pool and reduce wage comparisons.

During Hyundai/Kia's aggressive expansion in the past decade, with new assembly plants in India, China (2), Slovakia, the U.S. (2), Turkey, and Russia, Mobis built new plants nearby, sometimes following the not-too-close siting logic and sometimes in closely proximate supplier parks. Hyundai modeled its new assembly plants in China and India on its newest Korean plant at Asan Bay, and the supporting Mobis plants followed a similar replication strategy. Furthermore, Mobis manufactures its modules almost entirely for Hyundai (the exception is a contract with Chrysler) and, thus, is guaranteed considerable business; it is heavily dependent on Hyundai's sales, but also does not face competitors.

Supporting Hyundai's rapid global expansion to become the fourth-largest automaker, Mobis became the tenth-largest global automotive supplier, with sales that grew from \$1.7 billion in 1999 to \$14.4 billion in 2010. Mobis' profitability exceeds that of Hyundai Motor; its profits increased 50 percent year-on-year from 2009 to 2010, reaching \$1.6 billion. The great increase in the number of Hyundai vehicles on the road provides high demand for aftermarket parts; as I've mentioned, this is a high margin business that subsidizes R&D investments at Mobis.

We visited the Mobis plant, built in 2003 and located 12 kilometers from Hyundai's Asan Bay assembly plant, in the fall of 2005. All chassis, cockpit, and front-end modules for Asan Bay are made in this plant, at unit volumes of 300,000 per year. The modern facility is nonunion and staffed with contract workers from five different agencies, with staggered contract lengths so that turnover or contract renewals affect only a subset of the workforce at any one time. Wages are about two-thirds of the level paid at Hyundai's unionized assembly plant.

We also visited the Mobis plant in Montgomery, Alabama in 2006. Two different instrument panel modules as well as chassis modules were being built there for the Sonata sedan and Santa Fe SUV, with 150 minutes of lead time before sequenced delivery to Hyundai's assembly plant, 12 miles away. Opened in 2002, volume had reached 500,000 modules per year, with assembly lines and quality procedures virtually identical to the Mobis plant near Asan Bay. Wages for the 850 employees at the nonunion plant started at \$10.50 per hour and increased to \$15 per hour over two years, compared with wages at the Hyundai plant that started at \$15.60 per hour and increased to \$23.60 per hour. Both Mobis plants were clean, well lighted, and spacious—in contrast with other Korean supplier plants we saw in both countries.

Design and R&D collaboration

In its early history, Mobis was simply assembling components in the same manner as a Hyundai assembly plant would have done. But it has moved steadily toward more integrated module designs, with particular attention to reducing the weight and number of parts as well as better integrating the multiple functions embedded in each module.

To understand how Hyundai/Kia and Mobis think about achieving design gains from production-defined modules, I did interviews at the R&D facility of Mobis in Korea in 2008, 30 kilometers from Seoul

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and not far from Hyundai's R&D center. A chassis engineer described how Hyundai benefits from Mobis taking over the manufacturing of modules and then explained why it is a challenge for Mobis to benefit from module production to the same extent:

> 'Chassis modularity is not as beneficial for Mobis. We need to develop our own components. Otherwise, if we get components from suppliers, those costs are very clear to the OEM and we don't control them. We can only manage labor cost in that situation. So we are trying to develop our own electronics to control all functions in the module—suspension, ABS, power steering—to get the benefit of software-based integration and receive higher margins.'

From its founding, Mobis has emphasized building capabilities to achieve greater design modularity. Initially, Mobis entered into technology alliances with Bosch, Textron, and Siemens Automotive. Over time, Mobis has steadily increased hiring into its R&D function, growing from 150 engineers in 1999 to 700 in 2007. Its stated R&D goals are to progress rapidly from modules done mainly for assembly and logistics to functionally integrated modules characterized by reduced weight and number of parts, increased convenience of assembly, efficient inventory management, and cost savings.

Mobis also aims to be a technology innovator in its modules. This is facilitated by the close relationship between Mobis R&D and Hyundai R&D. As a Mobis manager explained:

> 'We have a lot of useful overlap in knowledge. Thirty to 40 percent of our engineers come from Hyundai, with lots of experience in car design. This makes communication with the OEM design engineers easy. The remaining 60 to 70 percent of our engineers are from component manufacturers. This helps us understand both sides—vehicle and component. Hyundai's system engineering capability is good, but they don't know the details of components. Mobis engineers can provide this knowledge linking.'

A project on electronic controls illustrates how closely Mobis and Hyundai work together:

> 'For unified electronic controls in the chassis module, we have a software team and a hardware team working together on this, located in the same office, talking all the time. Our software engineers are from electronics companies like Samsung and LG and we are using their techniques for software. We need to get lots of information from Hyundai and Kia—body data, engine characteristics. This is very easy for us with Hyundai because we are family—this is very difficult with other OEMs.

Collaboration is also necessary for problems like NVH (noise, vibration, harshness):

> 'We can't address NVH issues within chassis alone: it is tied to many other aspects of product design. When we have NVH issues, Hyundai and Mobis engineers meet frequently to resolve them.'

Thus, the design trend is greater levels of interdependence within these modules over time (as the number of parts is reduced, each part carries more, not fewer, functions) with continued interdependence **across** module boundaries for product performance criteria like NVH that are emergent and systemic. The paradox is that the performance of these 'modules' increases as they become more internally integral in terms of product architecture and as increased learning about cross-module interdependencies leads to an ever-more-integrated organizational architecture.

External customers

Although Mobis' sales are dominated by Hyundai, it seeks to diversify its customer base. Its most notable success to date was winning a 2006 contract to provide the front-end module to the Jeep Wrangler produced at Chrysler's Toledo, Ohio, plant; Mobis built a new plant nearby to support sequenced delivery. The relationship with Chrysler expanded in 2010 when Mobis landed a \$2 billion contract to supply front-end and rear cradle modules for the Jeep Grand Cherokee; it reopened the closed Detroit plant of a U.S. supplier for the needed proximity. So far, Chrysler is its only non-Hyundai group customer. Developing new customers has proven difficult, according to a Mobis senior executive:

> 'The module customer and the module supplier need a long-term business relationship, like Hyundai and Mobis—that way, we know we can invest. With an outside OEM, it is very difficult to know if we can invest. When we are asked to bid, we need to think about how long a relationship may be possible. We have a 10-year relationship with Chrysler in their supplier park. If Chrysler wants a change after that, they have to buy the plant back from us.'

In this executive's view, there is another necessary condition:

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> 'Mobis wants to expand its business to other OEMs, but first Mobis needs to have control over component suppliers and over module design— now both are owned by Hyundai. Without this control, building a general business isn't so easy.'

This executive explained that Mobis decided to bring development of some technologies inside in order to do more integration, e.g., proprietary work on air bags, brake systems, steering devices, headlamps, and unified electronic control software. Another motivation is that 'developing advanced technical capabilities is very important for Korea.' He said they would not keep these technologies vertically integrated indefinitely, mindful of the advantages of working with external suppliers to keep pace with technological change. Thus, while the tightly integrated relationship with Hyundai will be subject to disintegration pressures, it is likely to remain stable for some time.

Analysis

The framing of the modularity initiative at Hyundai and Mobis was multifaceted. Adopting modules at Hyundai was initially given a production rationale. At the same time, pursuing design improvements within modules was presented as a primary source of Mobis' future competitive advantage. By including long-term design innovation in the cognitive frame while also aggressively pursuing short-term production gains, Hyundai and Mobis managers justified a high investment in R&D and in integrated organizational arrangements that would move modularization-as-process forward.

Mobis was initially created on the production rationale that Hyundai, in adopting modules, would benefit from the organizational separation of manufacturing activities aligned with the module boundary. The three modules that Mobis builds all follow the industry's production-oriented definition. Hyundai, thus, accepted an already-established level of modularity-as-property and, through Mobis, pursued the manufacturing advantages this could provide. (These are exactly the same as those identified in the historical account, i.e., there is no evidence that Mobis found new manufacturing advantages to exploit.)

As its module business has grown, Mobis increasingly emphasizes the 'design innovation' framing of its modularity strategy. Indeed, Mobis presents its Just-in-Sequence modularity system as a 'third revolution' for the automotive industry, following Henry Ford's moving conveyor line and Toyota's Just-in-Time system—both production process innovations. The commitment to this strategy is cast in a long time horizon, well beyond other OEMs. These process innovations are framed almost entirely as arising from the relationship between Mobis and Hyundai, which was established in the change of organizational architecture that kicked off the modularity initiative.

From its inception, the relationship between Hyundai and Mobis has stayed closely integrated. The equity cross-holdings and governance structure, the frequent interaction of Mobis and Hyundai engineers, and the sharing of design tasks between Mobis and Hyundai R&D make this a quasi-vertically integrated relationship, marked by tight interpersonal and organizational ties across firm boundaries. Far from a reduced amount of coordination between OEM and supplier, collaboration between Hyundai and Mobis has intensified over time. Module designs remain closed, proprietary, and customized by model; Mobis' limited foray into working with another customer (Chrysler) has not shifted module specifications toward industry standardization.

What Mobis and Hyundai are doing together is not revolutionary; both production gains and design gains are logical outcomes of incremental improvement processes. What is most striking in their collaboration is the patient pursuit of module-level design innovation within the confines of production-defined module boundaries under conditions where standardization prospects are low, facilitated by tightly integrated organizational arrangements that foster learning-oriented modularization processes.

DISCUSSION

A concept such as modularity that can be simultaneously presented as source of the increased pace and extent of innovation, the surge of outsourcing/offshoring, and the feared loss of capabilities and advantage by incumbent firms and developed nations is powerful indeed. It is this very power that has made modularity into a Rorschach test; observers may discern the shape of whatever they are most inclined to see amid its murky outlines. Paying attention to the antecedents of decisions to pursue modularity-as-property, to what is learned from modularization processes, and how 'modularity'-in-frame influences the interaction between property and process is a priority in order to progress beyond

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Table 2. Ford case

	Modularity-as-property	Modularization-as-process	'Modularity'-as-frame
Antecedents	Production-defined modules, following industry usage; reinforced by supplier park experiences.	Suppliers ask to bid on design at module, rather than component, level.	Outsourcing manufacturing to suppliers to take advantage of lower labor costs, improve quality, reduce Ford's assembly plant complexity.
Key aspects of initiative	Define entire vehicle as 19 modules, each one a subassembly of many physically proximate components fulfilling different vehicle functions. Move quickly to pursue design innovations within modules. Implement more modules in each new vehicle program.	Debate within Ford about whether design and manufacturing knowledge and tasks should stay inside or be outsourced to suppliers. Executives/managers want big supplier role, engineers are skeptical. Suppliers seek autonomous design role, resist Ford's 'shadow engineering.'	Analogy drawn to computer industry. Relying on supplier expertise to increase design innovation. Sharing capital risk, reducing coordination with suppliers. Achieving cost savings, quality improvements and more and faster innovation. 'Put expertise in the supplier base where it should be.'
Consequences	Modules as defined can be optimized for production (costs sometimes higher), but design gains difficult to achieve due to high interdependencies across modules. Few new modules adopted due to cost and functional performance concerns, so entire modularity initiative is abandoned.	Supplier proposals for modules difficult for Ford purchasing to evaluate. Suppliers propose design innovations, but don't understand all components and interfaces well enough. Limited interaction between Ford and suppliers, beyond monitoring, due to expectations of supplier autonomy. Few supplier proposals adopted.	Viewed as a valid strategy, with poor implementation due to skill and knowledge shortfalls. For Ford, needing better systems engineering/integration capabilities. For suppliers, needing higher level of engineering talent, more systems knowledge of all interfaces with all components; lacking expertise in understanding customers, warranty and repair.

this confusion and indeterminacy (Kotabe, Parente, and Murray, 2007). Here I compare the two automotive case studies and draw out the implications for modularity research and for global architecture of the multinational firm.

Comparing Ford and Hyundai modularity initiatives

I summarize my analysis of the Ford and Hyundai modularity initiatives in Tables 2 and 3, identifying antecedents, key aspects, and consequences with respect to modularity-as-property, modularization-as-process, and 'modularity'-as-frame. I compare the two cases in Table 4, pointing out common features as well as differences.

As shown in Table 4, the two modularity initiatives arise at roughly the same time (1999 to 2000) and both start from the production-based module definitions already prevalent in the industry. Both set strategic goals that link modularity to outsourcing, and both begin outsourcing the production of large subassemblies to suppliers before they have fully crystallized their plans to pursue design modularity. Both have shifted their cognitive frame from components to modules and anticipate that performance advantages on multiple dimensions will result from this shift. Both recognize that product architecture changes need to be linked to changes in inter- and intraorganizational arrangements. Finally, both come to understand the need for OEM and suppliers to have a high level of knowledge of all components

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Table 3. Hyundai (Mobis) Case

	Modularity-as-property	Modularization-as-process	'Modularity'-as-frame
Antecedents	Hyundai reorganizes after Asian financial crisis, decides to adopt industry standard modules, seeking production advantages.	Mobis is spun off as separate parts subsidiary, given module responsibility.	Organizational separation of Mobis from Hyundai Motor will provide cost savings (lower labor costs), more flexibility, more speed in supporting Hyundai's rapid global growth. (Hyundai perspective)
Key aspects of initiative	Focus on three modules common in industry (chassis, cockpit, front end) using industry's production- based definitions, pursue long-term design gains within module.	Close governance ties, close proximity, frequent interaction of Mobis and Hyundai engineers allows progress on design integration.	Doing only production tasks for Hyundai brings limited benefits to Mobis. For competitive advantage, Mobis needs to innovate for better design integration within module. (Mobis perspective)
Consequences	Rapid growth of Hyundai and Mobis, plus high margins from Mobis' aftermarket parts business support high investment in R&D. Production gains achieved, slow but steady progress on design gains.	Recognition that a high level of information exchange and interaction between Hyundai and Mobis is needed for design gains in modules; cautious addition of new customers.	Mobis needs to gain more control over module design and over (lower-tier) component suppliers to make further design progress; should do more proprietary technology development. Long time frame needed to achieve this. (Mobis perspective)

and interfaces related to modules—although this awareness comes slowly to Ford (only at the end of its modularity initiative), while it emerges earlier at Hyundai and Mobis.

The company cases differ primarily in the cognitive 'modularity'-as-frame that spurred and informed each initiative, affecting module definition, strategic goals, the lessons drawn, and the extent of mirroring of product and organizational architecture. Each 'modularity' frame sets a particular direction for the initiative and a particular pace and sense of the necessary time frame for achieving strategic goals.

Ford drew on a computer industry analogy to frame 'modularity' as a way to change the division of labor between OEMs and suppliers and, hence, industry structure. These ambitions of Ford's CEO and senior managers, building on production experiences already underway with a few modules at supplier parks, drove an immediate partitioning of the entire vehicle architecture into modules. Under guidance of Ford's cross-functional modularity task force, newly identified modules were given production-based definitions, following the pattern set by existing modules. Ford's senior managers and strategy staff expected that suppliers could immediately begin to work autonomously on module designs on the basis of these definitions, thus moving quickly toward the modular organizational arrangements that would mirror the product architecture choices. Chief engineers, it was also expected, would adopt more and more modules with each new vehicle development project. That these expectations of achieving modularity-as-property were not fulfilled both confirmed the skepticism of Ford's engineers and reflected their close monitoring of supplier efforts and unwillingness to adopt supplier module proposals.

Hyundai, in contrast, initially emphasized the production advantages of separating module manufacturing made possible by the acquisition of Kia and the creation of Mobis, focusing on three modules already well established in the industry and moving quickly to high-scale implementation at a time of

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Table 4. Ford and Hyundai (Mobis) cases compared

	Common	Ford	Hyundai (Mobis)
'Modularity'-as-frame	Both see significance in shifting frame from component level to module level in terms of achieving multiple performance advantages.	Applies computer industry analogy: modules developed by autonomous suppliers as a way to reduce coordination costs, speed innovation, share risk. Focus on achieving modularity-as-property.	Applies historical auto industry analogy: modules as next big production process innovation, after moving assembly line (Ford) and JIT (Toyota). Close organizational relationship of Hyundai and Mobis seen as source of lower costs, more design innovation. Emphasis on modularization-as-process.
Module definition	Both start with production-based module definitions common in auto industry, i.e., physical chunks of proximate components that map to different vehicle functions.	Defines entire vehicle as set of 19 modules. Some are well established at industry level (though not standardized) and outsourced, others are newly conceptualized as modules and still vertically integrated.	Keeps primary focus on three well-established modules, e.g., chassis, instrument panel, front end, that will be produced in separate Mobis plants. Established in Hyundai's production system during period of rapid globalization.
Strategic goals	Both link modularity initiatives to the separating of production and the outsourcing of large subassemblies and to pursuit of design improvements.	Move quickly beyond outsourced production to implement 19-module architecture. Invite suppliers to submit module design proposals. Urge chief engineers to put modules into new vehicle projects. Prioritize reliance on supplier expertise, supplier autonomy.	Pursue production gains first for three core modules. Over time, realize design gains through high R&D investments and close coordination, frequent interaction between Mobis and Hyundai engineers. Maintain exclusive relationship, with Hyundai as only (primary) customer. Decision to develop most new technology within Hyundai and Mobis.
Lessons drawn	Both come to understand the need for both OEM and supplier to have high level of knowledge of all components and all interfaces.	Barriers to modularity seen as evidence of capability shortfalls at both Ford and its suppliers, rather than lack of emphasis on mutual learning through modularization processes.	Gains from modularity seen where integrative organizational processes between Hyundai and Mobis and internal technology development bring design improvements. Expecting difficulties in developing modules with other OEMs/suppliers.
Mirroring of product and organizational architecture?	Both recognize that product architecture changes need to be linked to changes in (intra- and inter-) organizational arrangements.	**No.** Expects product modularity (definitions that identify thin crossing places) to allow organizational modularity (low coordination with suppliers), but these expectations are frustrated. Initiative is abandoned.	**Yes.** Expects product modularity (with production-based definitions) will allow production-based organizational separation, but that design gains will require integrated OEM-supplier relationship given functional interdependence across modules. Making gradual progress toward design gains focused on more integration **within** modules.

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global expansion. 'Modularity' was framed as an industry innovation in production process; Mobis asserted that it would be the third 'revolution' of automotive manufacturing, joining lofty predecessors (Henry Ford's moving assembly line and Taiichi Ono's Just-in-Time production system).

In the Ford case, all parties involved focused on achieving modularity-as-property, including executives who sought more agility, better ROA results, and more (and faster) innovation from outsourcing module design and production; product development and purchasing managers who anticipated great reduction in coordination costs and scale economies from industry standardization of modules; and suppliers who hoped to move into a new role as autonomous providers of innovative design proposals. Even the engineers and manufacturing managers who were most skeptical about supplier capabilities didn't so much question the vision of mirrored modularity in both product and organizational arrangements as they cautioned going slower and advocated closer monitoring. None of the participants emphasized the potential gains from a modularization process of understanding interdependencies across components and module boundaries. Even when the initiative was shut down, the collective attribution was to inadequate capabilities for reaching modularity-as-property, rather than to a process failing.

Meanwhile, for Hyundai, the primary framing for the initiative was modularization-as-process, arising directly from its origin in a major change in organizational architecture, i.e., the creation of Mobis in the turbulent period after the 1997 Asian currency crisis. Mobis, as it spun off from Hyundai Motor, was very central in the OEM's organizational structure and in its sense of key competencies. Both Hyundai and Mobis executives saw the value of quasi-integrated organizational arrangements from the beginning. But it was Mobis managers and engineers who realized over time that solely manufacturing modules offered them little long-term benefit. Achieving design improvements to boost the Mobis share of value-added would require deepening the knowledge-intensive exchanges between Hyundai and Mobis engineers. Accordingly, interactions among Hyundai and Mobis R&D engineers, i.e., those with systems integration expertise and those with component expertise, respectively, **intensified** after Mobis was established as a separate organization, the reverse of what is generally forecast when organizational architecture becomes more modular.

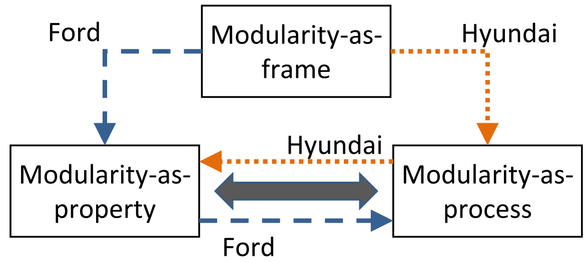

Figure 2. Modularity as property, process, and frame

The 'modularity'-as-frame identified in these cases—each cognitively influencing attention, information processing, interpretation of events, and legitimacy of contested perspectives—powerfully affected the direction, focus, and pace of each initiative, as shown in Figure 2. Ford's 'modularity' frame, based on a computer industry analogy and focused on speedily achieving modularity-as-property, created barriers to learning that impeded modularization processes. Hyundai's framing of 'modularity' as an automotive process innovation requiring integrative organizational arrangements kept Hyundai and Mobis engineers engaged in modularization-as-process and alert to long-term opportunities for design improvement. While the relationship between modularity-as-property and modularization-as-process is still bidirectional overall, the predominant frame applied in each case gave more weight to one of the two directions in the dynamics of each initiative.

While Ford's initiative sought mirrored modularity in both product and organization and failed to achieve either, Hyundai and Mobis had a different experience. The integrative expertise developing between Hyundai and Mobis was a good match to inherent technical characteristics of the modules being manufactured because these physical chunks contained bits and pieces of many different functional systems whose other components were distributed around the vehicle. The more a Mobis module 'knew' about other modules and components and overall requirements for the vehicle, the better it would work. Mobis engineers needed that breadth of knowledge, which they got from sitting with Hyundai engineers; in turn, the Hyundai engineers learned much more about component technologies.

It is in this regard that the Hyundai case, which at first appearance looks like a classic misalignment story of integrated organizational arrangements linked to modular product architecture, can be

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reinterpreted as supporting the mirroring hypothesis. Modules defined for production weren't actually all that modular from a design perspective; in fact, their blend of integral and modular characteristics could even be said to tilt toward the integral end of the spectrum. But as such, the quasi-vertically integrated organizational relationship of Hyundai and Mobis was well-matched to the product architecture. Note that the direction of influence in this case was from a change in organizational architecture—a consequence of Hyundai's restructuring—that created favorable conditions for Mobis to explore changes in product architecture, shifting over time from a production focus to a design focus, all within the confines of existing production-based module definitions.

Implications for modularity research

Much research approaches modularity as something that inherently resides in a product or organization, i.e., as a stable property that, once identified, can be applied as a label. I argue here that this viewpoint is naively deterministic and incomplete. Strategies for technological development don't simply arise from technical attributes of the product architecture or from how development processes are carried out, but rather are shaped, often dramatically, by the cognitive frames that firms bring to bear. The Ford case, in particular, shows how much the analogy of the computer industry shaped the 'modularity' frame to anticipate a particular path to achieving 'modularity-as-property.'

While it is always challenging to assess the extent of modularity-as-property for a complex, multitechnology product, the automotive case supports Fixson's (2005) argument that function-to-component mapping should be evaluated **separately** from interface coupling. IMVP researchers, when developing these case studies, applied Ulrich's (1995) ideal-typical definition to what the automotive OEMs and suppliers were calling 'modules' and concluded that they didn't deserve the name since there was no one-to-one mapping of function to component. Here, in the historical account, I present a revised perspective that highlights automaker motivations for pursuing outsourcing, which constituted separation along a production-defined boundary. The initial focus on outsourcing was not related to modular production *per se*, but it did influence the production-based definition of modules; emphasis on module design emerged only after this definition was well established. Fixson's (2005) approach helps make the sequence of events in the auto industry's emergent focus on modules more comprehensible.

With respect to the extensive literature on the 'mirroring hypothesis,' this account offers qualified support, but also a challenge. The automotive case is somewhat confusing, including to industry participants, because what they call a 'module' is difficult to separate from a design perspective, i.e., relatively integral, due to functional interdependencies across its boundary, while being easy to separate from a production perspective, i.e., relatively modular, due to the minimal difficulty of achieving one-step installation at the OEM's assembly plant. To call something a 'module' that is actually mostly integral would appear to set up a classic misalignment of product and organizational architecture, with the organization responding to the misleading label and choosing modular organizational arrangements, i.e., low coordination, that doesn't fit what the integral product architecture needs to be effective.

However, as I have argued, once differences in the intended purposes of modularity are taken into account, it is possible to see a mirrored match here rather than a misalignment. Automotive 'modules' are easy to separate for production and, organizationally, they are so separated; meanwhile, these same 'modules' are difficult to separate for design, so organizationally (e.g., at Hyundai and Mobis) integrated arrangements are established.

But I do not take this as complete backing for the mirroring hypothesis. There is little support in this industry case for *a priori* expectations that a shift toward modular (integral) product architecture will lead inevitably to modular (integral) organizational architecture. Indeed, as noted, this context seems highly likely to display the phenomenon that greater modularity, particularly of design, will emerge only as the *ex post* consequence of integrated organizational arrangements. Static cross-sectional assessment of product and organizational architecture in search of matched mirroring can generate misleading interpretations, while patient longitudinal tracking of the movements of product and organizational architecture (and how they relate to each other) can provide a better source of insight.

With respect to the boundaries of the firm, Baldwin's work (2008) on 'where do transactions come from' highlights the contingent reasons why tasks involving dense and complex transfers of

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information should be located in 'transaction-free zones' where transaction costs don't overwhelm the coordinative capacity of the system. Our mental image of a 'transaction-free zone' is often a firm (Kogut and Zander, 1996) where culture, shared identity, and management practices facilitating motivation, skill acquisition, and adaptability can boost capabilities for effective coordination. But here, and in other research (see MacDuffie and Helper, 2007), I find it is not firms that are the most reliable 'transaction-free' zones but rather that quasi-integrated organizational arrangements prove to be the most effective means of knowledge integration for design improvement. Future research could potentially identify the conditions under which a firm really is the best 'transaction-free zone' versus when quasi-integrated relationships with suppliers provide that opportunity.

This research speaks to Campagnolo and Camuffo's identification (2010) of opportunities to advance the modularity literature: (1) it explicitly incorporates a life cycle perspective on the evolution of module definitions and the interrelationship of production and design; (2) it pays close attention to the OEM's system integrator role as a barrier to modularization processes and a source of stability underlying persistent integrality; (3) it attends to performance issues, acknowledging that not all technically feasible modular designs will be adopted if their performance lags more integral designs; (4) it questions the unidirectional causality of the 'product designs organization' assumption and, hence challenges technologically determinist views of the consequences of modularity; and (5) similarly, it shows that product and organizational architecture are not necessarily directly correlated, but may have different trajectories for their interrelationship, due to different starting points and emergent misalignments.

Implications for global architecture of the multinational firm

This research can also inform how global firms think about the strategic uses of modularity. When outsourcing production and/or design activities in pursuit of the benefits of modularity-as-property, such firms may make the mistake of believing there is a technologically determined path leading toward inevitable outcomes, i.e., that this action will reduce production costs and speed innovation as global suppliers apply their specialized expertise to rapid improvements in the components going into key modules, allowing the firm to focus just on those tasks (e.g., R&D; high level product architecture) that are core to its competitive advantage. Instead, a multinational firm should approach both globalization and modularization as quasi-experimental learning processes that can provide ongoing data on how well capabilities are being extended into new countries, how successfully technical tasks are being transferred to other firms, and what knowledge it needs to maintain to oversee these externalizing activities.

When global firms view their efforts to decompose complex problems and to understand interdependencies as ubiquitous and perpetual, they are more likely to see how the learning processes of modularization can result in more integral, as well as more modular, products and organizations. This is especially true as new players, many from emerging markets, enter the auto industry value chain (Kumaraswamy *et al*., 2012). The fact that quasi-integrated organizational arrangements advance these learning processes when considerable interdependencies persist across module boundaries suggests paying attention to proximity of design activities between OEMs and suppliers in global locational choices. Planning for thick communication across organizational boundaries may be particularly important when systemic characteristics important to product performance are unpredictably emergent from cross-module interdependencies.

Generalizability and limitations

The research is primarily a single-industry case study, underpinned by implicit (and sometimes explicit) comparisons to the computer industry. While we originally made that choice because of how often during our automotive data collection the latter's highly modular product and organizational architecture was invoked, I do so here to highlight 'polar types' and to establish a basis for predicting what will happen vis-à-vis modularity in other industries. Asking whether an industry is more like automobiles or more like computers is a good first step, particularly since the latter has been overused as a generalizable analogy.

Automobiles are an extreme example of a multi-technology complex product that is difficult to characterize under a single label. While some claim that assessment of such product architecture is only reliable if done at the component level of analysis, this

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research highlights the value in examining the entire product and seeking to understand those systemic characteristics that emerge from component-level interactions. Thus, component-level and full product-level investigations are complementary; both are essential.

This research looks closely at what the auto industry chose to define as 'modules,' yet the process of modularization ubiquitously and perpetually affects all components and subcomponents at all levels in a product hierarchy. Future research could study modularization processes at various levels, departing not from what industry participants define as a 'module;' but rather examining any occasion on which managers and engineers make decisions about function-to-component mapping and the potential for separability. For example, in this same context, such an expansion of scope could examine functional systems that *aren't* physically proximate but are still designed with clearly specified interfaces to manage interdependencies with other functions, e.g., the safety system (Whitford and Zirpoli, 2012).

Finally, this research demonstrates the importance of paying heed to the multiple purposes to which 'modularity'-as-frame is applied, and how different its influence can be if it directs attention primarily to modularity-as-property versus modularization-as-process. As noted earlier, a primary focus on achieving modularity-as-property can constrain attention to the learning from modularization-as-process; accordingly, a primary focus on modularization-as-process can also reduce the salience of the goal of reaching a high level of modularity-as-property, instead creating a trajectory that leads to greater integrality. Framing effects, thus, help explain the often divergent findings in modularity research.

CONCLUSION

I examine three different but interrelated aspects of modularity to analyze product architecture initiatives in the global auto industry, in search of broader strategic lessons for global firms. Modularity is a property of the architecture of a complex system; modularization is a process that involves ongoing learning about interdependencies among elements in that system, i.e., where boundaries can be drawn and interfaces specified to create 'thin crossing places' between modules; and 'modularity' is a cognitive frame that affects strategy by prompting a particular dynamic—and directionality—in the interplay between property and process. I provide an industry history to document how the idiosyncratic definition of automotive modules emerged, and I analyze two company cases, at Ford and Hyundai, of modularity initiatives that both started from this definition but played out very differently.

The contributions of this research are fourfold. First, I demonstrate the crucial importance of examining the antecedents of a module definition, which constitute the earliest stages of the intertwined dynamic between property and process. Different trajectories are triggered depending on how a module is defined, due to path dependence at the firm or industry level; the choices of an 'architect' targeting a particular stage of the product life cycle; or negotiation among different interests. In the automotive case, the production-based definition of a module arose from the production logic of separability, but once established, it created difficulties for advancing design modularity.

Second, I show how powerfully 'modularity' as a cognitive frame can shape the interplay between property and process. Even when departing from the same production-based definition of modules, the Ford and Hyundai modularity initiatives displayed different dynamics due to Ford's emphasis on speedy achievement of modularity-as-property and Hyundai's expectation that it would only be able to go beyond production advantages to achieving long-term design gains by emphasizing modularization-as-process through integrated organizational arrangements with Mobis.

Third, I highlight factors that create barriers for modularity initiatives and can lead to persistent integrality, particularly from the reciprocal feedback between product and organizational architecture and the influence of potentially conflicting production and design goals. Automobiles have a stable, long-standing dominant design and many interfaces are well understood, but certain performance criteria cannot be predicted in advance due to complex interactions among functional systems and the consumer and regulatory requirements the product must satisfy. Understanding of these interdependencies emerges only as iterative cycles of design decisions occur. Furthermore, transaction costs may favor keeping a production or design activity inside an OEM, while emergent technical issues may create a requirement for OEM system integration knowledge beyond a supplier's capabilities. Thus, even where component interfaces can be well specified, systemic

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interactions and associated cost and capability considerations may render difficult the transfer of production and (especially) design responsibilities to a supplier. Overall, these cases provide evidence that the process of achieving modular design in automobiles is likely to be slow and only partially attainable, at least with the current dominant design.

Fourth, I provide a fresh look at the mirroring hypothesis—which predicts a convergence over time in product and organizational architecture—based on distinctive features of this context. The case studies demonstrate that what progress has been made in moving toward modular design in the auto industry has arisen within tightly coupled, quasi-integrative organizational relationships, showing that industry structures and organizational architectures do not necessarily map to, or evolve toward, technological architectures. Indeed, in the Hyundai case, the organizational design choice to establish quasi-integrative relationships between OEM and supplier came well before the modest movement toward greater design modularity that those arrangements made possible. 'Organization designs product' is as much an explanation for this particular case study as 'product designs organization.'

Most significantly, I hope to drive home two lessons for modularity researchers: (1) calling something 'modular' imposes a powerful cognitive frame that is just as likely to obfuscate as to enlighten (particularly when not informed by context-grounded research); and (2) 'modularity' frames drawn from one context are an unreliable guide to what will happen in a different context. Even if a component or subsystem is called a 'module' to focus attention on its potential separability and managed via 'modular' organizational arrangements, i.e., outsourced, careful scrutiny of interdependencies across the boundaries of that 'module,' to other components or subsystems, may well justify a classification closer to the 'integral' end of the 'modular-to-integral' dimension of product architecture. Witnessing separability and outsourcing and inferring the many attributes and meanings associated with ideal-typical 'modularity,' e.g., as in the computer industry, carries high risk of creating an analytic blind spot.

Managerial implications

Managers need to be aware of how modules are defined in their industry context, since these definitions influence the pursuit of modularity-as-property. Module boundaries defined for production don't necessarily coincide with the boundaries most favorable to design, and vice-versa; therefore, a module definition that privileges one may create difficulties for achieving the other.

Furthermore, managers often make the mistake of expecting that, having separated technical tasks, they can move quickly to a full separation of all related organizational tasks, i.e., that once they have outsourced work on a module to a supplier, they can rely on the supplier to proceed independently based on clearly stated module boundaries, interface specification, and functional requirements. This can be ineffective both because OEMs often need to retain the ability for system integration (Zirpoli and Becker, 2011) and because it is the dialogue about technical tasks **after** separation that often provides the insights prompting design innovations. A central paradox, therefore, is that modularity-as-property may emerge only after a modularization process that is interaction-intensive and quasi-integrated, the opposite of what we expect from a 'modular' organizational arrangement that mirrors the product architecture.

Thus managers should be careful not to overemphasize, in their framing of 'modularity,' the notion that modularity-as-property is inherent in a product and just needs to be identified through module and interface definition. Instead, it is better to de-emphasize whether modularity-as-property is (or is not) achieved and to emphasize instead modularization-as-process for learning about interdependencies within and across the boundaries of both product and organizational architecture. That knowledge, when developed together with suppliers, can provide the basis for sensibly refining the interorganizational division of labor, managing coordination costs, maintaining a balance across production and design goals, appropriately adjusting module boundaries, and improving module performance.

Finally, managers need a healthy respect for the power of 'modularity' as a cognitive frame, given the wide-ranging associations and macroconsequences it evokes. 'Modularity'-as-frame can become a cognitive trap in raising expectations of autonomous innovation, strategic agility, frictionless coordination, and industry scale efficiencies, a risk that grows all the greater when based on an analogy from a very different setting. To avoid this risk, managers should pay careful attention to context and contingencies, process and property, and learning how to learn from the barriers to modularity they face.

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