Modularity as a Strategy for Supply Chain Coordination: The Case of U.S. Auto

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***Abstract*—Companies across industries have admired the success of Dell Computersin using modularity as part of a mass customization strategy to achieve build-to-order and a streamlined supply chain. Many companies are attempting to emulate this successful model, including the American automotive industry. This paper focuses on how the auto industry has been attempting to move to modularity, in part, motivated by a desire to build cars to order. This movement has led to major changes in supply chain practices based partly on imitation of successful keiretsu models in Japan and a move toward modules. This study finds significant impact of modularity on outsourcing, product development, and supply chain coordination based on interviews conducted with automakers and suppliers from 2000–2003. Based on our interviews, we observe that modularity has accompanied a major reorganization of the automotive supplier industry. We identify two major issues that appear to block U.S. automakers from gaining most of the advantages possible through modularity. First, most modularity activities appear to be primarily strategically cost reduction driven, leaving the potential of modularity for mass customization largely untapped. Second, the shift in industry reorganization has not been accompanied by changes in the supply chain infrastructure to encourage long-term partnerships. We contrast this to the more gradual approach used by Toyota as it incorporates modularity on a selective basis and moves to a build-to-order model.**

***Index Terms*—Automotive, mass customization, modularity, outsourcing, product development, supply chain.**

I. Introduction

SINCE the 1990s, a growing number of companies have been craving the combined benefits of mass production (high volume, large quantity production) and product variety (offered through flexible manufacturing systems, product reconfigurability, etc.) at reduced cost and increased economies of scale. Mass customization, the term being coined by Stanley Davis [1] in his book, *Future Perfect*, became a popular business buzzword with the success of Dell Computers. By offering a large product variety specified by the customer with short assembly and delivery lead times, accompanied by reputable customer service support and attractive prices, Dell gained a key advantage over much larger competitors in the personal computer market like IBM, Apple, and Compaq. These companies offered product lines that gave the consumer little product variety, had lead times on the order of weeks or months due to backlogged orders, and were generally more expensive than the newer Dell platforms appearing on the market scene. What was Dell's secret? A successful mass customization strategy, incorporating the use of modular components and clever use of web-based configuration to order, is credited for Dell Computer's success. This strategy allowed Dell to compete on high volumes, low cost, and speedy delivery, and still offer a quality product with reasonable variety and reputable customer support. All this appealed to the needs and wants of the end consumer. With Dell being heralded as a textbook success story of the mass customization concept, how is it being applied in other industries? Other industries have seen Dell's success and have taken strides towards emulating aspects of Dell's mass customization system.

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A. Mass Customization and Modularity Benefits

The idea of mass customization has been heralded to provide several benefits. Pine [2] defines the goals of mass customization as providing enough variety in products and services so that nearly everyone finds exactly what they want at a reasonable price. It allows producers to customize products at low cost and allows customers to reap the benefits of customized products at relatively low prices [3]. Other benefits of mass customization include bringing customer specifications into the product design and achieving mass production manufacturing efficiencies. The standardization of parts and modules that occur in mass customization yields higher product quality and is conducive for repetitive manufacturing at low cost [2]. Another inherent benefit of mass customization includes the benefits of the build-to-order concept due to customer involvement, which minimizes finished goods inventories since customized products are not produced until customer orders arrive [4]. With all these heralded benefits, it is easy to see why mass customization carries such widespread appeal.

Several researchers have suggested that modularity is the critical factor in achieving customization at lower costs. Pine [2] argues that modularity is required for true mass customization in production. Ulrich [5] posits that the use of modularity could aid in increasing product variety as well as shorten delivery lead times. Baldwin and Clark [6] also propose that modularity is a means to partition production to allow for economies of scale. The apparent connection between the use of modularity and the successful implementation of mass customization is so prevalent that one researcher even states that, "To the extent that mass-customized goods are not modular, they may have to be scrapped." [7]. As a result, mass customization appears to presuppose product modularity, and the benefits heralded by a move to modularity would likely be realized in a move to mass customization.

Modularity is a trend occurring in many industries, including the computer, book publishing, and furniture industries, to name a few [6], [8]. It is a growing characteristic of the products of other industrial sectors such as the aeronautical and chemical industries as well [9]. Modularity is a general concept that describes the "degree to which a system's components can be separated and recombined, and it refers both to the tightness of the coupling between components" and the "degree to which… the system architecture enables or prohibits the mixing and matching of components" [8].

More recently, the automotive industry in America has been following this modularity trend. For example, when Jacque Nasser was President of Ford Motor Company, he invited Michael Dell in to consult with him on how Dell's mass customization approach, which combined a successful build-to-order model with the use of product modules, could be applied in auto to provide similar mass customization benefits to Ford. This had a profound effect on the strategy of the company, and helped make the U.S. auto companies aware of the benefits that mass customization had to offer.

B. The Automotive Context of Modularity

> "Modularity, systems integration, how much responsibility to outsource, and how to manage it, is THE question in the industry."

This statement comes from a Senior Systems Manager at a leading Tier 1 automotive supplier. This statement was his declaration during an interview regarding the emerging impact of modularity upon the automotive industry. He was referring to his customer's desire to source complete modules for a variety of reasons, including moving toward a build-to-order strategy. The modularity phenomenon is relatively new to the automotive industry, with the concept first being introduced to the industry in the mid to late 1990s [10]–[13]. Although a young trend, it has gained much consideration from executives in the industry. With the success of mass customized and modular products in the computer industry, there are many promises and perceived benefits to modularity that the automotive industry finds enticing. By adopting a modular strategy, IBM was able to achieve dramatic reductions in the lead times for designing and manufacturing its System 360 [14]. Dell Computers is a more current example of how the personal computer industry is exploiting the use of modules within their product lines to near-perfection. Not only Dell, but several other companies within the computer industry such as Compaq and Gateway have also used modularity as a way to simplify their product designs and assembly operations. In general, the product architecture of a personal computer is such that most of the components (e.g., floppy drive, monitors, hard disk drive) are separate modules that are manufactured and designed elsewhere by component suppliers. These relatively interchangeable modules can be mixed and matched and then brought together at final assembly in the manufacturing plant, packaged into a hard plastic casing, and shipped off to the consumer or retailer.

Near the end of the 1990s, the automobile, which began with an integral architecture (in which all the parts are interconnected and chunks cannot be separated out from the whole), became more modular due to various pressures. Fine [15], in his book, *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*, describes the competitive advantage Chrysler gained by moving to a modular strategy:

> "… we saw that Chrysler in the 1990s could be likened to Compaq in the 1980s. Through a modular product and supply chain strategy, each company managed to upset the advantages of much larger rivals and to trigger a chain reaction of events capable of altering dramatically the structure of the entire industry. In the case of Compaq and the fast-clockspeed computer industry, this series of events is already history. In the slower-clockspeed automobile sector, events are still unfolding before our eyes. In particular, the automobile is not as modular as the personal computer, and neither is the supply chain associated with the car industry."

In theory, it is not difficult to see the potential competitive advantage the successful use of modules might bring. Some original equipment manufacturers (OEMs) also seem "fully convinced that modularity is the answer to many of their supply chain/product development ills" [16]. Asserted one Product Director of a leading Tier 1 automotive supplier when asked about the future of modularity in the U.S. automotive industry,

> "None of the OEMs want to be behind on the modularity bandwagon. Like the PC industry, the auto industry is heading there as well… They (the OEMs and suppliers) are asking how much of the modules can they keep as basic as possible, and then just modify the exterior, or certain features. I think that's coming around."

Adopting the use of modules in automobiles in such a way as to achieve the time, cost, quality, and flexibility benefits associated with mass customization would be a phenomenon that could be considered a paradigm shift in the automotive industry; a paradigm where an OEM's purpose is to simply assemble parts of a vehicle like interlocking supplier-produced building blocks, and being put together as easily as Legos® or Tinker-Toys® for children.

The American auto industry began to move towards modularity in the mid-1990s, its proponents claiming modularity offered strategic benefits such as cost and lead time reductions and the ability to customize product lines in mass quantities; elements much in line with mass customization benefits. Since the late 1990s, corporate mergers, acquisitions, takeovers, and management reshuffling have characterized the U.S. automotive industry (OEMs and suppliers). The products themselves have seen an increase in the number of niche vehicles with innovative and trendy designs. Companies that position themselves to be leaders in the area of product development, and rapidly design and produce these vehicles with the latest amenities that an increasingly particular customer base demands, have a distinct competitive advantage [2], [6]. In fact, modularity lends itself well towards just such an advantage by harnessing an understanding of the efficiencies of product design and fabrication and tying them to strategic performance objectives such as time-to-market and product offering. Mikkola and Gassmann [17] summarize that modularity "refers to a *new product development strategy* in which interfaces shared among components in a given product architecture are specified and standardized to allow for greater substitutability of components across product families." In an industry as competitive as the automotive industry, where cost reductions and slim profit margins are the way of life, a strategic advantage in product development and design is key to survival.

Cost reduction is a major focus in manufacturing and supplied parts are one of the easiest targets. Suppliers are pressured with "target prices" set by OEMs that decrease each year and are expected to make a profit through relentless cost reduction. At the same time OEMs want a broader range of services such as building entire modules and delivering them in sequence right to the assembly line with near perfect quality. While pushing manufacturing costs onto suppliers by outsourcing the building of modules is an easy cost reduction target, the real benefits of modularity will come from the integration of product development, manufacturing process design, and supply chain coordination [15], [18].

The purpose of this paper is to better understand the process of moving towards modularity as part of a mass customization strategy, and its consequences using automotive as a case example. More specifically, this paper discusses the role modularity plays in changing product architecture and organizational form in the U.S. automotive context at three levels—manufacturing, product development management, and supply chain coordination. Automotive companies are striving to achieve the "X-day" car where "X" is a smaller and smaller number of days from when customers order customized vehicles to when they are delivered. And modularity appears to be an essential piece of the mass customization strategies forming in both the OEMs and Tier 1s in the U.S. auto industry. Modularity in the auto industry is arising as more than just a simple transfer of the modularity concept found in the computer industry. Issues concerning business, engineering, labor, and vehicle architecture are proving to be obstacles that are causing modularity within the auto industry to evolve into something different than its computer industry counterpart, providing a unique context for mass customization to take shape. And its implication for organizational design and supply chain structure causes modularity to have an impact on more than just the product architecture.

As modularity continues to evolve, both OEMs and suppliers will need to determine just how far they want to accept this new mass customization paradigm, and possibly even fundamentally rethink the way they design and produce automobiles. For that reason, perspectives from both the OEM and supplier sides will be investigated in this paper. The research method used in this paper incorporated semi-structured interviews (within the 2000–2003 time frame), with a broad range of industry participants, allowing in-depth understanding of modularity and its current form of practice in the U.S. today.

II. Research Questions

Since organizations are typically built around stable product architectures [9], this, in turn, defines key functional relationships, information processing capabilities, communication channels, and information filters. Once a dominant design is accepted, it is encoded and becomes implicit [19]. The automobile has long stood as a product with an integral architecture and the product development know-how associated with the automobile has become implicit and standardized in the auto industry for several decades. Historically, the automotive industry has been characterized by piece-wise component build of a vehicle whose basic product architecture is an integral one. While there have been documented successes in the computer industry with modularity [6], [20], [21], this does not automatically mean the modularity model can transfer easily to other industries such as automotive. First, there are some fundamental differences in product architecture that change the nature of the modularity challenge or even the definition of modularity [22]. Moreover, it is not clear in the academic literature what happens when an industry attempts to move nonmodular products to the modular context. Very little is known about the organizational design implications, both within the firm and across the supply chain, when companies that produce nonmodular products begin to move toward a more modular product architecture. Also, when an industry characterized by nonmodular products adopts modularity, the forces that enable and prohibit this change process need to be looked into. These considerations pose the following research question.

What is modularity and its impact on product and organizational design, within firms and across the supply chain, in the automotive context?

In the course of answering the main research question, other questions will also be answered, including the following:

1) What is emerging as the definition of modularity in the U.S. automotive context?
2) How does moving from a traditional component product architecture to a modular product change the nature of product development, manufacturing, and buyer-supplier relationships?
3) What forces enable and prohibit this change to modularity?
4) Is modularity a viable strategy for mass customization in the auto industry?

III. Methodology

The focus of this research topic is not on any one company, but on obtaining a broader perspective on the development of modules and the shift of responsibility in product development and program management from automakers to suppliers throughout the U.S. automotive industry. Data were collected via on-site, semi-structured interviews during the 2000–2003 time frame with Senior Engineers, Program/Engineering Managers, R&D Managers, and Program Directors within various OEMs and supplier business units. The use of interviews has been understood to be a valuable source of evidence when utilizing the case study approach [23]. According to Benbasat *et al.* [24] and Meredith [25], there are many advantages of using this methodology. First, the topic in question can be investigated in its natural setting and relevant theory can be created from observing actual practice. Second, the method answers the question of *why* (rather than just *what* and *how*) with a relatively full understanding of the nature of the phenomenon. Third, the methodology lends itself to early exploratory investigations where the variables are still relatively unknown and the phenomenon not well understood. Fourth, the approach allows for richness of explanations of various phenomena as well as

TABLE I
2000–2003 INTERVIEW LIST

System / Module	Company	People	Interview (hrs)
Cockpit Module	6	18	37
Door Module	2	7	7
Front-end Module	2	6	6
Suppliers	10	31	50
Automakers	3	8	11
TOTAL	**13**	**39**	**61**

for testing hypotheses in well-described situations [23], [26]. Due to these strengths, it was felt that the case study approach, with evidence collected through the use of open-ended and semi-structured interviews, would provide the richness of detail necessary to better understand the dynamics of modularity and mass customization being played out in a new industry context.

Pilot interviews were conducted with industry practitioners to ensure the relevance of the questions contained in the research question protocol. Among both the OEMs and suppliers, people involved with modules or systems integration projects were the most suitable to contact for the purpose of this study. The Engineers were better able to provide a detailed picture of the role of modules in product development, while the Managers and Directors were better able to provide a macro view of trends in the industry. In total, 39 different people were interviewed from among 13 different companies.

Regarding nomenclature, first-tier suppliers were defined as those that directly worked with and shipped parts to the Assembly divisions of the automaker. Suppliers to internal component divisions of automakers or suppliers that primarily supplied other outside suppliers were considered to be second-tier or lower, and were not included in the study.

The automotive suppliers interviewed in this study included suppliers responsible for subsystems within both the interior and chassis systems. Door panels, seating, cockpit, front-end chassis, and corner modules were modules and sub-systems produced by suppliers involved in our study. Table I summarizes the breakdown of the companies and individuals that were interviewed for the study.

Many of the questions asked during the interviews focused on a “typical” product development program and different issues affecting modularity such as labor, costing of modules, module design and assembly, product standardization, directed sourcing, resource and responsibility sharing, etc. The questions dealt with a variety of topics relating to the roles that both the OEMs and suppliers played during the product development process, from product concept, to package quotes, to production launch. Other issues such as designing in-house and product liability were also addressed. When conducting the actual interviews, impromptu follow-up questions were asked if the interviewee discussed a topic or event that was unfamiliar to the interviewers but was relevant to the formal questions stated in the research protocol. This allowed the investigators to capture streams of thought that would provide important insight and background when analyzing the interview data transcripts. Since interviews were conducted with both Tier 1 suppliers and OEMs, differing perspectives and alternate points of view were garnered on the issue concerning the role of modules in automotive product development. When no more new information seemed to be forthcoming, interviews were ended since that marked the data saturation point [27]. During much of the three-year time frame in which the interviews were conducted (March 2000 to March 2003 time frame), many of the suppliers and OEMs were mainly building modules designed by OEMs and suppliers were just experimenting with taking responsibility themselves for product development. At that particular point in time, not one supplier had in production a module in which they had taken the lead role in product development and program management. Again they were still in the early stages of this transition. Guidelines laid out by Miles and Huberman [28] were followed when analyzing the data transcripts to identify frequent themes and topics.

IV. RESULTS

A. *What’s in a Name?*

Duray *et al.* [3] argue that modularity is one of the key elements in defining a mass customization approach. They also postulate that mass customizers must utilize modular design to achieve manufacturing efficiencies that approximate those of standard mass produced products [3]. However, descriptions of approaches to the modularity dimension of mass customization on a product, process, firm, and supply chain level (especially with regards to artifacts in an industry transitioning from a mass production to a mass customization paradigm) appear to be sparse. As a result, it is important to address this issue since many companies are pursuing modularity in the hopes of shortening development lead-times as they introduce multiple product offerings and product variants at reduced costs and increased performance levels [17].

To better understand how modularity impacts various aspects of product development, it is necessary to observe how participants in industry view modularity in the automotive context. The definition of modularity is by no means straightforward. In fact, an extensive literature review of “modularity” found very different definitions throughout the literature [29]. It should be noted that this paper will not take a position on the definition of modularity but rather will describe the ways it is being used in the automotive context as a backdrop to the implications of this definition and the adoption of this form of “modularity” for the industry.

One of the first things observed in our study was that the term “modularity” in the automotive industry is not very well defined. It could mean a number of things, in addition to referring to attributes of the products themselves. Obviously, the term *modularity* would incorporate the notion of modular products, or, products that are made up of standardized parts and interfaces that can be reconfigured to propagate product variety [2]. On the other hand, in the auto industry at least, there are important attributes other than those directly related to the product that make up the modularity trend in the industry. For example, if an engineer or a manager in an automaker or automotive supplier is asked about what comes to mind when hearing the term “modularity," they will typically begin to discuss outsourcing and program management issues. Since a module in an automotive vehicle may incorporate a large variety of functions, components, and materials, it is most likely that a number of suppliers would be involved in producing a module (provided that the manufacturing of the module is outsourced by the OEM). If that is the case, then coordination and integration of these suppliers' activities and capabilities plays a crucial part in bringing the module together. Hence, the program management aspect of modularity is intertwined with the product attribute aspect of modularity.

Scholars and practitioners alike have proposed many definitions of modularity (general and automotive context definitions). Some of the following are definitions of modularity found in the literature.

- *Modularity*: refers to the degree to which a system's components can be separated and recombined [8].
- *Modularity*: a bundle of product characteristics rather than an individual feature, and different disciplines and viewpoints emphasize different elements of this bundle [29].
- *Modularity*: a particular pattern of relationships between elements in a set of parameters, tasks, or people; a nested hierarchical structure of interrelationships among the primary elements of the set [30].

There are also a variety of terms often used in connection with modularity. Phrases like "interchangeable components," "mix-and-match capabilities," "standardized interfaces," and "platform planning" all promote the re-use of some fraction of the product across product families or generations while "customizing" the remaining fraction [29]. This being the case, it is easy to see why so many people in the industry may have varying pictures in their minds when they hear the term "modularity."

As to what practitioners in the auto industry consider a module, there are differing answers. A Modularity Manager at one of the OEMs describes this lack of a common definition when she states, "Chrysler puts together a trim part and a panel, and they call it a module. Mercedes puts together 11 modules and calls it a vehicle. There seems to be no consensus on what is a module." To confuse the issue even further, the OEMs and suppliers are experimenting with modularity to varying degrees. In recent years, for example, there are instances of automakers using the modularity concept in both the design and assembly phases of vehicle cockpit development [31].

Following the modularity type classification proposed in [32], uses of these and other such modules could be categorized as *component-sharing* modularity and *component-swapping* modularity. Component-sharing modularity occurs when common components are used in the design of different products, and as a result, parts of a product can be "uniquely designed around a base of common components" [32]. Component-swapping modularity occurs when options are allowed to be switched on a standard product, and as a result, modules "are selected from a list of options that are to be added to a base product" [32]. Duray *et al.* [3] assign component-sharing modularity to the design phase of a product and assign component-swapping modularity to the assembly phase of the product cycle. With instances of modularity being utilized to varying degrees within both the design and assembly phases, there appears to be a lack of focus in addressing the modularity phenomenon industry-wide that makes it difficult to create much of the standardization necessary for further advancement of mass customization. If OEMs and suppliers in the automotive world are to coordinate their efforts and capabilities effectively to take advantage of modules, then a common working definition will be necessary for the proper communication of ideas, allowing for effective and efficient flow and sharing of information and processes.

B. Module Versus System?

Part of the difficulty in talking about modularity in the auto industry is distinguishing between a "module" and a "system." According to the dictionary, the traditionally accepted English definitions of both a module and a system are as follows:

Module: A standardized unit or component, generally having a defined function in a system; a self-contained assembly used as a component of a larger system [33].

System: A group of interacting elements functioning as a complex whole [34].

These definitions provide a starting point and a key insight. In automotive, at least as conventionally engineered, certain collections of parts can be viewed as self-contained, fitting the modular definition. For example, one can view a seat as a module. It is a "self-contained assembly and a component of a larger system." With some basic specifications on the interior and how the seat will be connected to the floor and perhaps the seat restraint system, the seat designer can engineer the seat relatively autonomously and then have it built and shipped in sequence to assembly plants. In fact, seat engineering by outside suppliers and building in sequence to the assembly plant has become common practice across the industry. But other parts of the vehicle are not so clearly self-contained. For example, the brake "system" is not a self-contained assembly that can be built in one place and then plugged in on the assembly line. It is a "group of interacting elements" that runs from the brake pedal to the wheels with fluid under pressure and is also connected up to the engine compartment. Similarly, the electrical system winds its way throughout the vehicle. So we need to distinguish between modules and systems, and systems often cut across modules making it impossible to autonomously engineer a module without considering its impact on a variety of systems.

One problem with the dictionary definitions alone is that it does not specify any minimum size or complexity for a module. One could argue that both an entire cockpit module (which is inserted into the vehicle body at the OEM's final assembly plant) and an airbag cassette module (inserted into the steering wheel at a supplier's plant) are one and the same. But there is clearly a difference in scope with these two modules. One is a large physical chunk of the car containing a vast array of interacting systems and components. The other is a much smaller physical bundle of only a handful of parts with only a few interacting components. If one were to take this example further, the program management aspect in coordinating even the design and manufacture of these two "modules" is much different. The cockpit module would require the design and creation of dozens of components made by about a dozen suppliers, with a lead supplier coordinating and integrating much of the program management effort. The airbag cassette module,

TABLE II
AUTOMOTIVE MODULE & SYSTEM PROPERTIES

Module	System
Made up of a *bundle of components and sub-assemblies* grouped together in the vehicle	Made up of a *grouping of sub-functions* existing in various parts throughout the vehicle
Defined by *physical architecture* of the vehicle (dependent upon packaging requirements)	Defined by *performed function* in the vehicle (dependent upon performance requirements)
Attachable / detachable from vehicle	*Integrated* into the vehicle
Often *contains portions* of several systems	Often *intersects throughout* several modules
Requires *static* linking of components and sub-assemblies to create the desired packaged bundle	Requires *dynamic* linking of components and sub-assemblies to create the desired function performance

on the other hand, could be designed and manufactured entirely in-house by a Tier 2 automotive supplier (e.g., TRW, Siemens) and then shipped off to another supplier who then incorporates the airbag cassette module into its cockpit module. The systems integration and program management expertise would not be needed to bring about the successful creation and delivery of an airbag cassette module. The program management capability, system integration competence, and technical expertise to bring about the cockpit module make its creation much less trivial than the airbag cassette module. And thus, to someone working with cockpit modules, the term "modularity" or "modules" may carry much different connotations than to someone working with airbag cassette modules.

So what are the different ideas that are conjured up when people hear these two terms in the industry? How do they define a module and a system? From our interviews, all the participants echo the notion that in a vehicle, at least, modules and systems intersect. Another shared view is that systems seem to be defined by their function; that is, by what they do—climate control, steering, electronics, or otherwise. Modules, on the other hand, seem to be defined by the physical packaging of components. None of the people we interviewed identified a module as something that performed a certain set of functions. Rather, a module was identified as a bundling of components and sub-assemblies that made up a certain physical entity. Table II provides a list of many of the different characteristics of modules and systems that were compiled throughout our interviews.

Based on the above descriptions garnered from practitioners in the industry, the diagram in Fig. 1 portrays conceptually the difference between modules and systems. The important thing to notice is that the module (represented by the solid rectangle) is intersected by various systems in the vehicle (represented by the dashed ovals).

In this specific instance, a cockpit module would house parts of several systems: steering, safety, climate control (heating, ventilation, and air conditioning), and the electrical display system (EDS). The cockpit module is the physical housing in which parts of these representative systems are contained, along with other physical components existing within the cockpit module. Conversely, the diagram in Fig. 2 conceptually portrays the module versus system difference from another perspective.

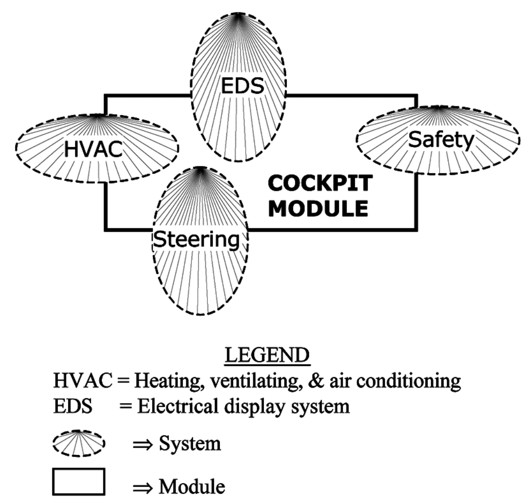

Fig. 1. Cockpit module example.

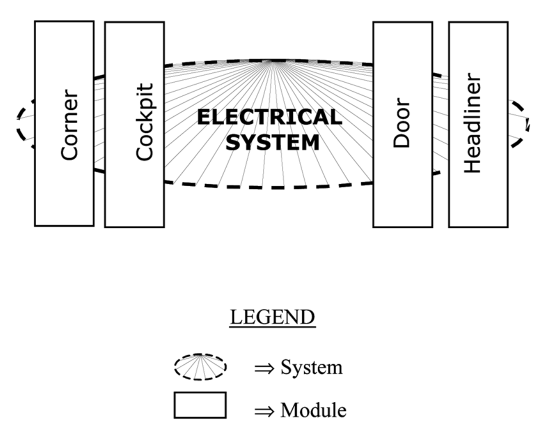

Fig. 2. Electrical system example.

In this situation, the electrical system cuts through several different modules: corner, cockpit, door, and headliner. As a result, the electrical system provides functions that permeate the various modules in the vehicle. Again, the modules and system intersect with one another, as in the previous cockpit module example. Based on the interviews, this is the basic understanding among practitioners in the auto industry.

Modules and systems do not overlap as congruently in automobiles as in the case of computers. This lends itself to a host of problems in defining a modular architecture for the automobile. Fine [15] explains that one of the successes of IBM's approach to the open architecture for the PC was that it allowed for the delineation of modules and systems to overlap in the product on the same lines. Hence, for example, the memory "system" became identical to the "hard disk drive module." By defining modules and systems in the personal computer along the same lines, it was fairly trivial to divide up and outsource major parts of the computer to outside vendors, allowing for the hoped-for benefits of cost, time, quality, and flexibility associated with mass customization to be realized. But in the case of the typical automobile, modules and systems do not overlap so well. As we have just described, major system functions often intersect through major parts of the vehicle, creating a confusing mesh of functions and components that is difficult to untangle. This confusion hinders the standardization and commonality of parts and part interfaces on a wide scale, making the benefits of mass customization harder to realize in the auto industry.

C. Approaches to Modularity

In considering the impact of "modularity" in the case of automotive, we have found we cannot restrict ourselves to product characteristics alone but must also consider the associated roles and responsibilities in the supply chain. When we consider both the physical product and "who does what, " we have found three basic configurations: the assembly module, design module, and integrated design module. As one Manager in a leading interior supplier explained to us:

> "There are three phases of modularity. Let us take a cockpit. The first phase is already there in the car plants where the cockpit is assembled offline. The second phase adds to this (suppliers) designing modules. The third phase consists of deep integration. The real benefits arise when you have deep integration of that product. This phase requires a lot of work that is not attainable in normal activities. If there are a lot of changes, it requires a longer cycle."

Similar distinctions between approaches to modularity or what we might consider levels of modular outsourcing arose throughout the interviews. Thus, we came up with an empirically derived classification that represents practices in the automotive industry and is not intended as a general classification of "modules." Putting together the various approaches to modularity that we identified in the interviews we came up with the following five-level classification:

1) *Traditional Layer Build (TLB)*—This is not considered a module, but serves as the base to compare to. For several decades, TLB has been the paradigm by which vehicles were manufactured. With this method, the entire vehicle is created piece-by-piece, layer-by-layer throughout the design, development, and assembly processes.
2) *Assembly Module*—This is the simplest and earliest form of module encountered in our study of the U.S. auto industry. With the assembly module, OEMs keep the responsibility for concept creation and design engineering, while components are either made in-house or outsourced to suppliers. The OEMs simply outsource part of the assembly process from within their own plants and outsource it to the supplier plants. This approach to modularity was the most common form encountered in our investigation between 2000–2003.
3) *Mature Assembly Module*—This approach goes one step beyond the Assembly Module in that the OEM is still responsible for the creation of the concept and controls the engineering. However, design engineering is often done with involvement (to varying degrees) of the supplier. In this approach, components are generally outsourced to various suppliers, often with direct control of the OEM, and assembly of the module is done at the supplier plant.
4) *Design Module*—The modules in this category can be described as a collaborative effort between the OEM customer and the module supplier. Concept creation is shared between the OEM and supplier, design engineering is done by the supplier, components are outsourced to the supplier, and assembly of the module is done by the supplier. At the time of the interviews no supplier had a Design Module in production, but they were making progress in this direction, in some cases just starting a program based on Design Modules. From our observations, this is where the bulk of the U.S. auto industry was moving as of 2003.
5) *Integrated Design Module*—These are rare or nonexistent in practice depending on how stringently defined, and it may be some time before it is realized in the global automotive industry. It is the most ambitious type of module from a design, performance, and production point of view. As in the case of the Design Module, the supplier and OEM share concept creation responsibility, with the supplier doing much of the design engineering, component production, and assembly of the module. However, to allow for the integration of various components and functions within the module, the supplier must also be able to control much of the sourcing issues that the OEMs now control. If such integration of parts and functions can occur, the Integrated Design Module will yield itself to large chunks of real estate in the vehicle that combine components and functions throughout the automobile outsourced to what some call 0.5 tier supplies (a notch above the first tier).

The classifications above are broad categories of approaches to modularity observed within the industry. Thus, even within one category, there are variations. Table III summarizes the above descriptions based on descriptions gathered from interviews with various OEMs and suppliers.

D. Modularity and Manufacturing Outsourcing

The interviews conducted for this study occurred during the years 2000–2003; the same time when much of the modularity and mass customization adoption process was unfolding in the U.S. auto industry. As a result, the researchers were fortunate enough to capture several details regarding many of the important issues surrounding the phenomena such as manufacturing outsourcing, product development, and supply chain coordination. The history of these issues in the U.S. auto industry could be pieced together from the various interviews with automakers and suppliers. When modularity first appeared in the U.S. auto industry in the mid 1990s, the OEMs were the most interested

TABLE III
APPROACHES TO AUTOMOTIVE MODULARITY

Classification:	Traditional Layer Build	Assembly Module	Mature Assembly Module	Design Module	Integrated Design Module?
Module Type:	Generation 0	Generation 1	Generation 2	Generation 3	TBD ?
Brief description:	•Concept by OE •Design by OE •Engineering by OE •Validation by OE •Components made in-house or outsourced •Assembly at OE plant.	•Concept by OE •Design by OE •Engineering by OE •Validation by OE •Components made in-house or outsourced •Assembly at supplier plant.	•Concept by OE •Design by OE & supplier •Engineering by OE & supplier •Validation by OE & supplier •Components outsourced to supplier •Assembly at supplier plant.	•Concept by OE & supplier •Design by supplier •Engineering by supplier •Validation by OE & supplier •Components outsourced to supplier • Assembly at supplier plant.	(Same as Design Module description + Supplier has discretion to control sourcing issues ?)
Product example:	Standard cockpit	Assembly cockpit module	Design & Assembly cockpit module	Design cockpit module	Integrated cockpit module
Status:	In Production	In Production	In Production	In Transition	Does Not Exist
Appearance in Production:	1950s – Mid 1990s	Mid 1990s – Late 1990s	Late 1990s – Early 2000s	Early 2000s – Present ?	2005 - 2010 ?

in this movement. Wanting to shirk design and production responsibility, the OEMs began a concerted effort to push this responsibility onto the supply base. The OEMs hoped to get the benefits of the resulting outsourcing achieved by IBM and Dell, relegating the automotive OEMs to more of an "assembler" role as time went by.

From the recollection of many of the interviewees, the first major responsibility to be outsourced to suppliers was that of parts fabrication—what was described in Table III as Assembly Modules. Hoping to outsource some of the work in their plants, it seemed relatively easy for the OEMs to remove part of their assembly processes and move them into supplier facilities. By giving out some of the assembly work and equipment, the goal of the U.S. automakers was to remove certain assets from their books, making the automakers more attractive investments to Wall Street investors. The OEMs were pushing modularity onto their suppliers first, hoping for productivity and profit gains, as well as cost reduction to take advantage of the lower wage rates of suppliers.

In addition to the immediate financial benefits of modularity, the "Big 3" (General Motors, Ford, and Daimler Chrysler) were all moving in the 1990s toward "lean manufacturing" based on the Toyota Production System. The ultimate aim was the idea of the mass customized, build-to-order car, which reduced lead-time to the point consumers could pick their vehicle configuration and have it built and delivered to them. Modularity became part of that strategy. If outside suppliers could take responsibility for building large physical chunks on separate assembly lines, the following things could happen.

1) It can be more efficient to build a module that then gets plugged in. For example, a cockpit module can be constructed in a one-piece flow cell and moved and turned about to add components. In contrast, on the assembly line the worker is maneuvering in a small space inside the passenger compartment and laying down under the cockpit and there is a lot of waste in the assembly process-not to mention ergonomics problems.
2) The supplier plant can specialize in the building of a module and develop expertise in flexible manufacturing so they can actually build to order. The assembler need only send out a broadcast of what module it needs next and the supplier can build it and ship it in sequence to the assembly line. Much of the complexity of build to order gets pushed onto the supplier.
3) In general, assigning self-contained tasks to more specialized teams simplifies the management problem. Smaller, product-focused cells are a hallmark of lean manufacturing.

Historically, there were a number of highly visible successful cases of this model, mostly in South America. Volkswagen was the first to go as far as bringing suppliers right into the assembly plant to build modules as close as possible to the point of fit on the main assembly line. Later Ford took this approach in Brazil in its "Amazon" project. General Motors working with Lear (an interior supplier) made history by actually bringing Lear workers right onto the assembly line to "dress out doors" as part of the Blue Macaw project [35]. While Lear had a special spot inside the plant, 16 suppliers built modules on-site at the broader complex and delivered these in sequence to the assembly plant.

In fact, the U.S. automakers grew so excited by the potential of these early experiments that they began to tell their suppliers they needed the capability to build complex modules. This was in fact a major factor in the mergers and acquisitions of the late 1990s as companies sought to acquire the expertise and manufacturing capability to build complete modules. However, what was not anticipated were two major barriers to moving ahead with the module approach—union resistance and short-term financial accounting systems.

In the mid 1990s, American automakers adopted the perspective that mass customization and modularity seemed to make great economic sense. Suppliers also wanted the increased business. However, in 1999, it became clear that modularity was being perceived negatively by the United Auto Workers (UAW). [1] The UAW saw modularity as a threat since it was seen as the outsourcing of jobs. As one GM engineer described:

> "… the UAW issue was the main reason why modularity was so sensitive. One of the things talked about was short mainlines and multi-vehicle plants, and keeping a common bill of process, so that for example the doors are all built the same and the layer builds are common. All that would have driven you to more modularity…. And the UAW saw that as the outsourcing of jobs so it became a political issue for them. They were certainly not gaining jobs on import companies like Toyota, Mercedes, Honda, etc. The UAW was not gaining jobs there, so they had to hold onto U.S. company jobs."

When a former General Motors Vice President announced at an industry press conference that General Motors was planning to follow a full-blown modularity strategy in its new "Yellowstone" project to make Cadillacs by pushing out of their product pipeline more modular vehicles and investing in the creation of modular plants, the UAW threatened to go on strike. This was one year after the UAW labor strikes at GM in Flint, MI, which resulted in a tremendous financial loss for GM in 1998. Eventually, the Vice President was moved to a different position in the company, and much talk that initially surrounded modularity disappeared from the industry. When we interviewed a Modularity Manager at one of the OEMs, we discovered that even at the Vice President level of the corporation, there was much bickering about the future of modularity for the company. Should the company follow a full-blown modularity strategy? Should the company disregard modularity altogether? Or would the best solution be, at least for the present, to pursue modularity, as one former Modularity Manager in one of the Big 3 stated, "when the business case makes sense?" This Manager went on to explain the following:

> "Whether or not it is a barrier to something good for the company's profitability, the UAW is a force to be reckoned with. The OEMs are practically obligated to use UAW labor. In fact labor contracts lock OEMs into a certain hourly employment level and laid off workers were being paid close to their full wages when working. So we come back to the economic justification issue. How can you justify modularity even based on head count reduction if more money must be paid to suppliers and there is not a corresponding reduction in internal labor?"

"When the business case makes sense" then turned over control of modularity to the finance community. Modularity shifted from a business strategy to an option on a case-by-case basis as the business case could justify it. Unfortunately short-term justification of modules is not easy. Managers' and Directors' performance reviews are generally tied in the U.S. auto companies to the short-term profit they make on each vehicle program. As the same former Modularity Manager explained,

> "Our Program Managers' and Directors' bonuses are based on the profit of their vehicle. If their variable costs go up, it screws up the bottom line, and they don't look good even if it is good for the company. A lot of the things our suppliers are proposing are not necessarily good for the program, but are good for the company. This is a case where the incentive structure is hindering modularity."

E. Modular Products, Modular Organizations

From the interviews, we learned that as OEMs began to pursue mass customization and outsourcing of assembly modules, it became clear that some product redesign was required. Things like cockpits had to be designed such that all of the parts could be connected to the instrument panel offsite and then "plugged in" to the vehicle on the assembly plant. In some assembly plants, installation of the cockpit became a one station operation done within the cycle time of the line (as little as a minute or two). Thus, the product began to be modularized in its design.

From our observations, a similar transformation was occurring in the organizational structure of the OEMs and suppliers. The original vertically hierarchical form of organization that the U.S. automakers exhibited before the days of modularity reflected the integral nature of the vehicle architecture. Most every component and sub-assembly was designed and manufactured in-house by the large U.S. automakers, enabling the OEMs to retain much of the technical expertise required to manufacture vehicles. With an integral product architecture, the level of task interdependence was high, as the case between divisions or suborganizations in an integral organization form when they are collocated in close physical proximity and have frequent meetings to coordinate the pieces of the vehicle to fit together.

Hovever, both the product and organization form appear to be changing as modularity has entered the U.S. auto industry. The U.S. automakers have been moving down the road and "modularized" themselves by turning more into vehicle assemblers and outsourcing much of the manufacturing and assembly of the parts of the vehicle. Automakers are outsourcing much of the design and assembly work required to produce vehicle modules. The goal is to engineer the vehicle such that the level of task interdependence between different modules and between the module and the vehicle is low. This would allow for modularizing the organizational design such that OEMs could provide target prices and specifications to "mega-suppliers" who engineer the module relatively independently of the OEM and other suppliers. These results are summarized in Table IV.

As there are a variety of approaches to modularity, we noticed that there are also corresponding degrees of interdependence occurring between the firms in an automotive supply chain. Interdependence describes the extent to which organizations depend on each other for resources, materials, and information to accomplish their tasks. Thompson's [36] classic categorization characterizes these forms of interdependence. The traditional form of vehicle production (i.e., layer build) requires the

[1]The full name of the union is International Union, United Automobile, Aerospace and Agricultural Implement Workers of America (UAW).

TABLE IV
PRODUCT AND ORGANIZATION SIMILARITIES (MODULAR VS. INTEGRAL)

	Modular Product	**Modular Organization**	**Integral Product**	**Integral Organization**
Form:	Loosely coupled components or subassemblies, each usually self-contained	Loosely coupled companies or divisions, each possessing different competencies	Deeply linked components designed to optimize the functionality of the product as a whole	Collocated divisions / departments working in close conjunction
Mode of Linking:	Bolts, screws, and other separable fasteners	Contractual arrangements or strategic alliances	Shared product material and deeply integrated into product	Mergers and acquisitions and vertical hierarchy
Level of Interdependence:	Low	Low	High	High

simplest form—*sequential* interdependence—between organizations in a supply chain. With sequential interdependence, the work is of serial form, with parts produced by one organization becoming the inputs for another organization. This is often the case with long-linked technology, which refers to the combination in one organization of successive stages of production; each stage of production uses as its inputs the production of the preceding stage and produces inputs for the following stage. Demands on inter-organizational communication are relatively low since each organization simply performs its work according to standardized rules and procedures. Each supplier in the supply chain mediates between other suppliers in the chain, and work for the most part independently of other organizations. Communication tends to be sporadic and not constant, only necessary at critical points, such as contract negotiations, requirement changes, and occasional supervision. Coordination is mainly done by a central player, in this case the OEM, who coordinates through plans, targets, rules, and procedures. A bureaucratic organization structure can be effective in managing sequential interdependence.

In reality, the supply chain has not been that simple in automotive for decades. Because of the complexity of the vehicle, the automotive OEM receives numerous components, sub-assemblies, and in some cases design input from several different supply chains, all converging at the OEM's vehicle assembly plant. The type of interdependence exhibited between these different supply chains is *pooled*. With pooled interdependence, work does not flow between organizations in differing supply chains. Instead, each supply chain deals with its workload as a set of self-contained tasks. Each supply chain works independently of other supply chains, but depends on a pool of resources, for example, the funding from the OEM or schedules put out by the OEM. Demands on inter-organizational communication between companies in differing supply chains is still low, like sequential interdependence, since each organization simply performs its work according to standardized rules and procedures and limited input from one source—the customer.

With thousands of parts in a vehicle, both types of interdependence are present. Suppliers in lower tiers pass on information and parts to other suppliers and ultimately to the OEM, and the OEM carries the bulk of the program management responsibility necessary to coordinate each separate supply chain and maintains each point of contact with outside suppliers; multiple nodes, if you will. This traditional form of the automotive supply chain structure will be termed a sequential-pooled structure to represent the sequential interdependence within one supply chain, and the pooled form of interdependence between differing supply chains. Both types of interdependence are managed centrally by the OEM in a top-down, hierarchical manner. This is depicted in the model shown in Fig. 3.

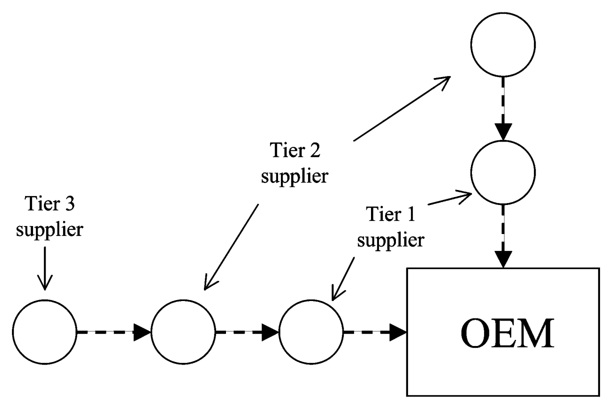

Fig. 3. Sequential-Pooled Automotive Supply Chain.

But with the coming move towards mass customization and modularity, an interesting metamorphosis of the U.S. automotive supply chain structure is happening. The program management and coordination roles are shifting from OEMs to lead Tier 1 module suppliers, the largest of which are usually termed *integrator suppliers* [12], [13]. When observing the supply chain structure of the automotive supply chain in the case of the module supplier or integrator supplier, there is a reduction in the complexity of coordination requirements carried out by the OEM and an increase in the complexity of coordination requirements carried out by the supplier. The number of supply chains reaching the OEM decreases with the presence of modularity since each major module is handled by a separate module supplier, who then ships the finished module to the OEM at the vehicle assembly plant.

The integrator supplier has an added job of collocating some of the people and resources of these various supply chains in-house, and managing their activities. Thus, the integrator supplier must manage a *reciprocal* form of task interdependence with the suppliers that are collocated in its facilities. With reciprocal interdependence, the inputs of one supplier (e.g., communication, feedback, intellectual resources, shared

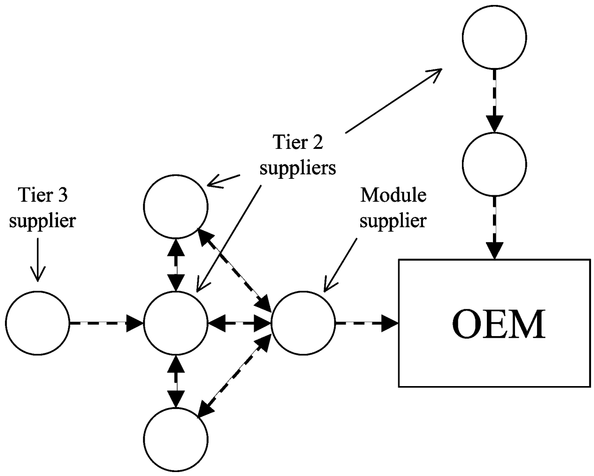

Fig. 4. Sequential-Reciprocal Automotive Supply Chain.

protocol, etc.) are the outputs of another supplier on the same project, and vice versa. The engineering decisions of each supplier working with the integrator supplier influence the other parties, and they all work together to create the final major module which the integrator supplier then delivers in finished form to the OEM. Reciprocal interdependence tends to occur in firms that generally incorporate *intensive technologies*, which provide a variety of products or services in combination to a client. Management challenges are far greater in the case of the integrator supplier since reciprocal interdependence requires that departments work together intimately and be closely coordinated. The firm structure of the integrator supplier and the firms that work with it must allow for frequent horizontal communication, daily interaction, and adjustment. When considering one or more tiers below the module supplier or integrator supplier, the interdependence between different supply chains is again pooled, as in the case of the traditional automotive supply chain explained earlier. Fig. 4 depicts the sequential-reciprocal form of the automotive supply chain seen in the modularity context described above.

It is clear that OEMs are putting themselves at great risk when they outsource so much of the intellectual property in the vehicle. When a vehicle is a bolted-together set of modules, the quality and even appeal of the vehicle will depend at least as much on the module suppliers as on the OEM. And OEMs have not moved toward modularity in the Dell Computer sense of mass customized mix-and-match parts. It is not as feasible to replace the Visteon-made cockpit in a Ford Taurus with a Magna-made cockpit as it is to replace one hard disk drive with another in a laptop. The cockpit can be built separately but still is highly customized and integral to the vehicle. Thus, OEMs are investing a great deal in specific assets of suppliers—specific engineering skills, tooling, manufacturing capability, program management skills—when they engage a supplier to engineer and build modules.

The make versus buy decision as exemplified by transaction cost economics would suggest in this case of high asset specificity that pure market mechanisms for control will not work [37], [38]. The hierarchy is needed to be sure suppliers do not take the power they gain once they get the contract and use it to extract high "rents" from the automaker. Moreover, there is a good deal of proprietary intellectual property that must be protected when suppliers are designing core parts of the OEMs vehicle.

As we learned from the interviews, the solution to this has been for suppliers to develop separate business units or divisions that focus on each OEM's business. This allows suppliers to cater to the various requirements of specific OEM customers on mass customization and modular programs. Thus, Magna for example, has a Daimler-Chrysler (DCX) business unit with its own executive staff, sales staff, marketing specialists, program managers, and engineers dedicated to DCX programs, as it has for other OEMs. In essence, firewalls are created between business units so proprietary information on DCX programs cannot be leaked to the Magna engineers working for another OEM. The business unit exists or goes out of business based on the business of the single customer; as a consequence, it can be highly controlled by that customer. In essence, the automaker is outsourcing yet retaining the control of the vertical hierarchy in its dealings with the business unit.

However, from our point of view, this structure has not solved all of the OEM's problems. Just as within any hierarchical organization there are effective and ineffective management systems. Management of these external business units takes a high degree of skill. For one thing, the module as mentioned is still customized and intimately connected to the rest of the vehicle. And since systems cut across modules in the typical vehicle, there is a great deal of engineering coordination required to make the modules and systems work together. In addition, the systems supplier is now coordinating other suppliers, including competitors, and that process must be managed. The interviews we conducted suggested that the emerging relationship between the American OEMs and "mega-suppliers" were anything but harmonious. In fact, the conflicted relationships of years past when OEMs treated suppliers as replaceable commodity manufacturers characterized these "new relationships" to a greater degree than the Japanese partnership model. Below are some of the examples of barriers in evidence.

F. Barriers to Effective Supply Chain Coordination

Through the course of the interviews, several barriers were uncovered which highlight some of the difficulties in moving the U.S. auto industry towards modularity. These difficulties serve as barriers that prevent OEMs and suppliers from realizing many of the expected benefits that would be generated from their mass customization and module program efforts.

1) Setting Target Prices (Soft Versus Hard Costs): One of the practices the U.S. OEMs learned from Japanese competitors was target pricing. In the old model, ,the supply side would set the price. Suppliers calculated their costs, added a desired profit margin, and went to market with a bid. In contrast, in the target pricing model, customers estimate what the market will bear, set a target profit and based on that calculate the cost of the vehicle that will allow them to make the profit. That cost is then broken down into the cost of components and modules. Suppliers are given a target price and then they must figure out how to reach the costs needed to achieve a profit. Suppliers, therefore, cannot control price but can only control costs.

Quite apart from modularity, the interviews suggested that American companies were seeking the cost savings but were not implementing the target pricing effectively from the perspective of suppliers. Japanese auto suppliers typically find the target costing process challenging but fair [39]. A lot of the practices of American automakers were simply seen as unfair. One supplier explained:

> "We have gone through a different target cost process for every group we deal with. If you are above target they cannot issue a purchase order. We have gone around and around and reached launch after major investments of cash without a purchase order. So we cannot get paid."

Another supplier complained how inconsistent one American OEM is in the target setting process:

> "If we meet the target too early in the design process they will change the target. So there is absolutely no incentive to make the target early. There is no target setting process. It is done differently every time. It even is different across programs within the same platform. It depends on who is in the room."

The way OEMs set the prices that they are willing to pay suppliers has a major impact on what investments the supplier will be willing to make in R&D and innovation in the product. Before modules, OEMs used historical data to set target prices. "Last year we paid you X and this year we expect that you cut your costs through improvement activities so we will pay you X minus 5%." This may be defensible, but what happens when the OEM is no longer buying X but is buying X as part of a module and asking suppliers to design and engineer the module and asking suppliers to manage the project?

Undeniably, one of the largest barriers to modularity is the lack of any compensation provided for these additional costs of doing business when taking on responsibility for modules. Throughout the interviews, suppliers complained about the misalignment between how they (the suppliers) felt the costs of developing modules should be assessed and the way the OEMs were actually assessing the module costs. This dilemma was explained in detail by a Product Development Manager working for a leading interior supplier.

> "When the customer receives it (a module), they just see the overall cost; that the sum of the components is more expensive. They don't see the value-add. They can achieve more throughput. There are savings on complexity, warranty savings, weight savings, labor savings, and space savings, but those are "soft costs." A huge problem is having the customer take the soft costs and giving that as a target to the supplier as a target. They only know the hard costs."

2) Conflict Between Supplier Outsourcing and Purchase Power—Directed Sourcing: Given that suppliers are taking responsibility for managing the program, meeting customer's target costs, and engineering the modules, who controls the sourcing decisions for the modules? If a supplier is going to take on program management responsibility, including managing other suppliers, and also responsibility for reducing prices based on cost reductions, then they would like control over the suppliers who build the components shipped to their plants. OEMs argue that if they can control the purchase of commodities they can get volume discounts across modules and subassemblies.

If the OEM possesses the sourcing power, and can direct the supplier as to whose radio should be used in the cockpit and whose heating, ventilating, and air conditioning (HVAC) system should be used, then the supplier does not have direct control of the bill of materials (BOM). And if the supplier does not have control of the BOM, then they do not have the capability to make complicated tradeoffs, for example, between material cost and internal efficiencies. As a result, the U.S. automotive industry is seeing a movement of the engineering and development responsibilities shifting from the OEM to the supply base, but yet there is still a limited amount of integration occurring in modules since the suppliers do not have full design control due to the fact that they do not have full control of the BOM. In one specific case concerning the cockpit module, we observed that a particular supplier was awarded the cockpit module assembly along with the instrument panel and the trim. The supplier, however, did not get awarded the HVAC and the wiring harness, they were sourced to other suppliers. An executive of the supplier explained:

> "I am not aware of a single supplier that has full sourcing authority over the whole cockpit. The OE will still direct the BOM. The supplier can manage material flow, but not make decisions on the actual material. We don't write the HVAC and audio specs. Those are driven by the OE. Even the Purchasing organizations are set up according to commodity programs. Purchasing is set up to buy commodities and parts, not modules."

Another negative impact of directed sourcing from a supplier perspective is the potential impact on confidentiality. Take the following situation described to us by one of the Managers interviewed in a leading interior supplier.

> "No one wants to have their core products integrated by another supplier. Those business issues are very real. There is the issue of competitive advantage. Rear seat entertainment versus audio head unit is a real case example. One of our global competitors was awarded the rear seat entertainment while we were given the audio head unit. We thought we were going to get the tech secrets from the rear seat entertainment supplier (our competitor), but the OEM insisted that it be the other way around; we ended up providing our secrets to the rear supplier."

3) Lack of Trust in Supply Base: A promise of mass customization and modularity is to decrease engineering workload and overall lead time as expert suppliers manage the development of their chunks. Yet, most of the module suppliers mentioned that both their test and validation workload has increased and the OEM's test and validation workload had not substantially decreased. Without modules, validation procedures apply at both the component and vehicle levels. With modules, validation procedures apply at the same component and vehicle levels and also at the module level. Despite suppliers' claims that validation procedures are no longer necessary at the component level, OEMs have been used to doing so and it is a way to increase their confidence in the module. OEMs lack trust in the validation capability of the suppliers. Multiple validations are a way to limit the risks of future defects.

Suppliers do not have enough experience in designing integrated modules yet. Most of them have just been trying to acquire the necessary knowledge for a whole module by acquiring specialized suppliers or merging with other suppliers. They do not have enough background to design a module with somewhat standardized interfaces. Consequently, every proposal of integration is more or less an innovation and comes from someone who has not been in the expertise area for a long time. As for any innovation, an assessment process is applied which is not always compatible with the OEM's program planning.

As a result some of the same OEM engineers who were responsible for the "module" when it was simply part of the vehicle engineered by the OEM are still overlooking the engineering now that it is an outsourced module. But they are doing it by looking over the shoulders of the supplier that ostensibly has responsibility, thus, referred to by suppliers as "shadow engineers." Arguably this is a transitional phenomenon until these engineers retire from the OEM or are otherwise phased out and until the suppliers are trusted with the engineering responsibility. But in the interim, because of these redundant activities, the OEM was not getting the expected cost savings internally and, thus, not willing to spend additional money for the extra supplier responsibilities. Suppliers for their part view the OEM engineers as meddling and time consuming.

4) Warranty and Liability: Contractual Issues: One of the greatest initial barriers to mass customization and the adoption of modularity in the auto industry was the issue of warranty and liability. The OEMs wanted to continue to shed more design and program management responsibility to the supply base. Accompanying this outsourcing of responsibility is the desire to push the warranty responsibility onto the suppliers as well. However, this move did not sit well with many of the suppliers that were interviewed in the study since it was seen as an increase in risk for the suppliers. There was also confusion as to who may end up bearing the bulk of the warranty costs. "If there is a warranty problem," asks one design engineer from a Tier 1 cockpit module supplier, "who pays the warranty? The cockpit module supplier?"

In the computer industry, Dell Computers, for example, obtains the parts for their personal computers from module parts suppliers, but if something goes wrong with the computer, Dell is willing to back up the warranty claim, even if the failing components is from one of its suppliers. Dell's approach to mass customization makes them willing to take the responsibility for the warranty issue and back up the quality of their product and product's components with their brand name. But in the auto industry, such practice is not the norm. Automotive OEMs want the supplier to be held responsible if a supplier's component or module fails on the field. This was clearly the case in the Ford/Firestone incident where Ford Motor Company blamed Firestone for its faulty tire design when it was discovered that several Ford Explorer trucks were flipped over due to failing tires, even causing some deaths.

Along with the warranty issue on repairs and parts replacement is the issue of safety liability. Who is liable for safety concerns if modules fail in the field? Is it the supplier that assembled the module? Is it the OEM customer who designed the module and installed it onto the vehicle? Ultimately this can become a battle between the OEM customer and the very module suppliers they are so dependent on for most of the product. One Director of Integration & Modules Engineering at an interior supplier explained it with the following example.

> "In the end, we have to have more liability at the suppliers. Here is one example. We make switches for one OEM, and there are issues with fires, and the fires were the result of system level things which we had nothing to do with. But it cost us $6 million. But we had to accept this and cost of the recalls because we couldn't afford to lose the OEM as a customer."

G. A Contrasting Approach to Modularity and Supply Chain Coordination: Toyota

The Japanese auto supply base is traditionally organized into "*keiretsu*," a network of manufacturers and suppliers that have equity ownership in one another as a means of mutual security. This network is often characterized by a great deal of parts outsourcing to a small number of closely knit suppliers who are given long-term contracts [39]. There is competition among suppliers but typically 2 or 3 suppliers make a given type of part and have 100% of the business for a given vehicle program. They are selected very early in the product development program, guaranteed the business, and become part of the extended product development team. First-tier suppliers take major responsibility for the engineering of subsystems and do their own testing. OEMs realize that they are dependent on the suppliers who have dedicated assets, like tooling and product development knowledge, which are difficult to duplicate. So they maintain control through direct ownership of a portion of the suppliers and interlocking boards of directors. As they have moved to doing more business with American suppliers they, like the Big 3, have insisted that first-tier suppliers set up divisions dedicated to them and build firewalls separating it from the rest of the supplier's business.

While Japanese companies may have purchased some smaller subsystems that might be considered modules (e.g., exhaust systems), they did not make the move to larger and more technologically intensive modules (e.g., corner modules or rolling chassis) until some years after than their U.S. competitors. Most of the business that the Japanese outsourced to their keiretsu supply base tended to be on the sub-assembly and component levels. They were steering away from the modular trend to give larger and larger chunks of vehicle real estate to their suppliers.

The Japanese have shown they are not to be underestimated when it comes to the adoption and implementation of modularity and mass customization. As of 2003, the Japanese had all but caught up to their American and European counterparts with respect to adopting modularity and mass customization strategies for their corporations. Toyota was in the midst of creating 13 or 14 keiretsu mega-suppliers, following more and more the Integrator Supplier model founded in the U.S. For example, in 2002, Toyota launched Advics Co., a joint venture in Japan with Aisin, Sumitomo Electric, and Denso [40]. Advics (which stands for *Advanced Intelligent Chassis Systems*) links brakes to suspensions and other ride and handling equipment. They supplied complete brake systems with the goal of $2 billion in global sales by 2005. While Toyota is the largest customer, they are going after American manufacturers' brake business and already have landed large contracts. They have the stellar reputation of Toyota and its suppliers for quality excellence and innovation behind them [40]. These new Japanese mega-suppliers have very broad technical and program management competencies, much like their U.S. systems integrator counterparts, and are already involved in the design, development, production, and assembly of modules. However, unlike the systems integrators in America, the Japanese mega-suppliers still belong to the keiretsu network, with the OEM maintaining redundant competencies to oversee the operations and development of the mega-suppliers. And by establishing new joint ventures with these suppliers, Toyota is taking a large portion of equity.

As Japanese OEMs, like Toyota, are moving toward a modularity and mass customization strategy, they are building on a much stronger foundation of effective supply chain management. A survey conducted by J.D. Power of automotive suppliers found that Nissan, Toyota, and BMW are the best North American automakers in promoting innovation with their suppliers [41]. Honda and Mercedes also finished above average in fostering innovation, while the DaimlerChrysler group, Ford, and General Motors all were rated below average. Yet while suppliers laud Toyota as their best customer they are often described as the toughest customer. We often think of "tough" as difficult to get along with or unreasonable. In Toyota's case, it means they have very high standards of excellence, and expect all their partners to rise to those standards. More importantly, they will help all their partners rise to those standards.

When Toyota started building automobiles, they did not have capital or equipment for building the myriad of components that go into a car and had to depend on suppliers to take risks and invest in capital. All that Toyota could offer was the opportunity for all partners to grow the business together and mutually benefit in the long term. So like the associates who work inside Toyota, suppliers became part of the extended family who grew and learned the Toyota Production System. Even when Toyota became a global powerhouse, they maintained the early principle of partnership. It views new suppliers cautiously and gives only very small orders at first to test the suppliers commitment and capability. They must prove their sincerity and commitment to Toyota's high-performance standards for quality, cost, and delivery. If they demonstrate this for early orders, they will get increasingly larger orders and become part of the family. Toyota will teach them the Toyota Way and adopt them into the family. Once inside, they are not kicked out except for the most egregious behavior. And simply switching supplier sources because another supplier is a few percentages cheaper would be unthinkable. As Taiichi Ohno, creator of the Toyota Production System, said:

> "Achievement of business performance by the parent company through bullying suppliers is totally alien to the spirit of the Toyota Production System." [42]

Toyota outsources over 70% of the components of the vehicle. But it still wants to maintain internal competency even in components it outsources [43]. These days a management buzzword is "core competency." Toyota has a clear image of its core competency but seems to look at it quite broadly [42]. This goes back to the original creation of the company when Toyota decided to go it alone instead of buying designs and parts of cars from established U.S. and European automakers. If Toyota outsourced 70 percent of the vehicle to suppliers who controlled technology for them and all its competitors, how could Toyota excel or distinguish itself? If a new technology is core to the vehicle, Toyota wants to be an expert and best in the world at mastering it. They want to learn with suppliers, but never transfer all the core knowledge and responsibility in any area to suppliers. So it is not surprising that Toyota is not willing to follow the Big 3 and outsource entire modules to "mega-suppliers" who come in at the lowest bid. Instead Toyota is setting up joint ventures with only its closest supplier partners to engineer and build modules. Not only do they have the confidence that their keiretsu partners understand their systems and philosophy and can be trusted but they have the added insurance of equity ownership and are learning along with their suppliers to maintain their internal core competence. In this way Toyota may be able to achieve a true integration of product, process and supply chain coordination as they move toward modular architectures.

V. Discussion

A. *Automotive Modularity and Mass Customization in U.S. Auto*

Researchers have proposed the general principles of mass customization as providing variety in products and services at a level such that customers find what they desire at a sensible price [2], and unique products manufactured to customer specifications without the advantages of economies of scale [1]. Although an agreeable concept, achieving true mass customization in the U.S. auto industry seems laden with difficulty.

In many of the interviews conducted, it was apparent that there was much focus on how to grasp the modularity phenomenon as it was unfolding in the U.S. auto industry. Even though automakers and their suppliers understood the importance of modularity to mass customization, not much emphasis was given to understanding how the voice of the customer could be better incorporated into vehicle design and production, another key dimension to a mature mass customization strategy [3]. Cost reductions seemed to be the primary driver for the outsourcing of modules occurring in the U.S. auto industry, not satisfying customer requirements per se. For mass customization to gain further ground among automakers, customer requirements need to somehow find their way into product offerings. The modularity movement in the U.S. auto industry deals much with the buyer-supplier roles in vehicle design and assembly. Technical issues such as how to cluster components in a cockpit module for outsourcing of assembly purposes permeated much of the interviews in our study. However, none of the people interviewed mentioned the importance of the customer perspective with regards to their approach to modularity. There appeared to be a greater emphasis on the cost and lead-time savings that modularity could bring to vehicle manufacture rather than on providing what the end-consumer really wanted.

In fact, in the auto industry, customer requirements hardly ever make their way into the product development value stream early on. As of 2001, only about 5% of the cars built in the U.S. were built-to-order [4]. For the most part, although the customer may be able to choose from a list of limited/standardized options, customer preferences at the point of order or sale are not used to guide design and production. The auto industry has traditionally relied on forecasted demand to estimate their product designs and production volumes. The Internet has helped facilitate the idea of "locate-to-order" where auto dealerships can search through the inventory from other dealerships within the company to locate the desired vehicle configuration, but even then, the customer is still faced with the choice of either choosing from stock or waiting several weeks for the vehicle to be built [4]. To make matters worse, a customer who purchases a vehicle that is already on the dealer's lot will most likely garner some sort of discount whereas a customer who orders a customized vehicle will wait several weeks and pay a higher price! Due to this disconnect from the voice-of-the-customer, customer requirements and desires are not directly brought into the product development value stream early on. At best, the automotive industry's approach to modularity and mass customization is a limited version of build-to-order.

Using the mass customization archetypes discussed in [3], automotive companies would most likely be classified as *modularizers* since customer specifications can be incorporated into the vehicle assembly and modularity is incorporated in the design and production stages. *Modularizers* "incorporate both customizable modularity in the later stages of the production cycle and non-customizable modularity in the design and fabrication stages of the production cycle" [3]. As a result, the U.S. automakers and their suppliers may not gain the maximum benefits of mass customization since they use modularity as a means for part commonality but not for product customization. The purchaser of a vehicle is offered only a limited degree of customization by being able to choose options such as paint color or trim level from a prescribed list.

Even if the voice of the customer were to be brought in more directly to automotive design, it would have to be done early enough in the product development process to make mass customization financially and strategically viable. A more mature adoption of mass customization practices would include not only the modular design of cars, but would also include a way to bring in customer preferred functional performance levels into the design and assembly of the product. Operationally, the use of dynamic and stable production and assembly processes would have to support the production of such customized modules. Supply chain requirements would also have to be rethought to take advantage of last-minute customer configured vehicles; from supply channels to distribution channels. Contemporary design, manufacturing, and supply chain paradigms, such as 3-D concurrent engineering [15], [18], could shed greater light on the support infrastructure that would need to evolve if the auto industry is to further benefit from modularity and mass customization.

With regards to firm level issues, mass customization application still needs to be thought through further. To more closely tie customer requirements to vehicle design and assembly, component and module suppliers need to be integrated into the mix. Several industries, including automotive, are so large and complex that it is critical to closely tie suppliers' product design and production efforts to that of the OEMs. This adds to the difficulty of incorporating the build-to-order approach of mass customization. The large geographic distances that separate many U.S. suppliers from their OEM customers, combined with the more short-term, adversarial, cost-cutting characteristics of the buyer-supplier relationship, only appears to frustrate any longer-term integration efforts necessary for greater mass customization across the automotive supply chain.

Auto manufacturers appear to be trying to harness the efficiency and operational benefits of mass customization through an industry-wide move towards modularity. But at the same time, they are doing little to incorporate the customer perspective. In the U.S. auto industry, modularity has made its way, in varying degrees, into product development, production, assembly, and supply chain considerations. Understanding that any strategy shift requires change, the U.S. auto industry has lagged behind in attempting to incorporate the voice of the customer into its value stream earlier on to gain more of the benefits of mass customization. There have been some limited attempts at bringing customization into vehicle assembly such as with Volvo's mutable wire harness which allows for customers to alter their electronic options through their dealer up to four hours prior to build [4]. But to fully realize more of the benefits of mass customization, one cannot focus only on modularity issues that affect product design and firm relationships. Even though some strides have been taken, ultimately, the U.S. auto industry still has ways to go before it can see further benefits in realizing the philosophy of mass customization; its promises of product variety, operational efficiency, and economies on a mass scale.

B. Modularity Considerations

Mass customization through the adoption of modularity offers opportunities for gains in efficiency, cost savings, quality improvements, and flexibility to move toward the build-to-order model that the auto industry is so anxious to achieve. The modularity aspect of mass customization has major implications for manufacturing, product development, and supply chain coordination. The modularity strategy in auto is intimately connected to outsourcing and the degree of responsibility given to outside suppliers, and, as a result, links mass customization to both strategic and tactical operations issues. We have identified a number of different approaches of modularity ranging from the simplest form where chunks of the vehicle that had been assembled on an assembly line are pulled off and built by suppliers who sequence the modules to the line to the most ambitious forms in which outside suppliers design, engineer, and market large parts of the vehicle that are then built and sent in sequence to the assembly line. This process is moving slowly and OEMs are maintaining a great deal of the engineering control over modules.

This control over modules permeates the relationship the OEMs have with the suppliers themselves. Throughout the interviews, we observed that U.S. automakers possess a large amount of ascendancy over their suppliers and are reluctant to share much of the cost burden as modularity is being introduced into the auto industry. OEMs are trying to outsource much of their module production and assembly to suppliers, focusing mostly on vehicle design and final assembly, as a means of cost reduction; shifting the cost burden for these processes onto their suppliers. There appears to be little initiative on part of the OEMs to share any financial burden even initially for the startup costs incurred during this transition. These characteristics would be consistent with that of an *exit* (or more adversarial) buyer-supplier relationship between the OEM and module supplier, as opposed to a *voice* (or more partnerial) relationship [44].[45]. However, when an industry that has traditionally been characterized by an integrated product (like U.S. auto) makes the transition to a more mass customized, modular product, much of the supply chain and infrastructure issues need to be thought through. The resultant outsourcing of labor and responsibility on the part of the OEMs, without requisite cost sharing and other support initiatives, hinders further adoption of modularity and realization of mass customization benefits.

The approach is similar across Ford, GM, and DaimlerChrysler. They desire to achieve the benefits associated with mass customization and to outsource modules to suppliers who are able to build up enough bulk and competencies in building modules in sequence, to engineer these modules, and to manage major programs. The Big 3 also insist that the suppliers set up internal business units dedicated to the OEM to maintain the proprietary information of the OEM, and to agree to aggressive target prices set by the customer and continue to drive down prices through the life of the program through cost reduction. They have experimented with a number of highly visible programs in which suppliers have taken over most of the program management responsibility for engineering and building the module. Some suppliers are even doing the marketing research to develop the concept for the module. For example, the outside seat supplier has more data and arguably knows more about the needs of the customer than the automaker. But the U.S. auto industry is slowed down by an ineffective supply chain infrastructure inherited from the early days when suppliers were treated as commodity producers and purchasing departments beat suppliers up for price reductions.

We saw a very different supply chain model in Toyota. While Toyota and other Japanese automakers have been far more cautious in embracing modularity and mass customization, they are building on a much stronger foundation of technically strong suppliers, integrated into the product development system, with expertise in lean manufacturing, who are treated as partners in the enterprise. Toyota has developed highly effective approaches to working with suppliers on product development in Japan and is bringing those practices to the U.S. While American OEMs are highly bureaucratic often imposing ritualistic rules and procedures, Toyota's processes make sense to suppliers and work.

C. Limitations of the Study

Due to the relative newness of the modularity and mass customization phenomena occurring in the U.S. auto industry, the case study methodology was adopted to investigate the research questions. As a result, the researchers were able to gather a considerable amount of detail regarding the adoption of modularity occurring in both OEMs and suppliers. However, due to the extensive use of interviews in the data collection process, some limitations to the interview methodology should be kept in mind when considering the observations mentioned in this paper.

One limitation to the study deals with the issue of response bias [23]. The majority of the interviews were conducted with automotive suppliers; only a few OEMs were willing to offer their perspectives. There are a few reasons for this. First, there exist far more suppliers than OEMs in the auto industry, making it more likely that a firm willing to be interviewed would be a supplier. Second, the barriers to entry in obtaining interviews with a supplier seemed easier to pass than those for an OEM. The interviews conducted at the OEMs had to be approved through multiple time consuming levels of accountability before obtaining a positive response. Reasons for this were unclear and might be explained by either differing levels of firm bureaucracy or degree of willingness to be interviewed on the research topic, among other factors. Regardless, the impression was that suppliers seemed more willing to be interviewed regarding the topic of study. It would have been more ideal to interview additional OEMs to establish greater consistency and validity of the anecdotal evidence regarding the OEM perspective. A third possible source of response bias stems from the interview contacts themselves. After the completion of an interview, the contact information of more individuals within the company was asked for from the people just interviewed. In so doing, it is plausible that some of the interviewees gave contact information of individuals whom they felt would agree with their perspectives on the research topic. Although the reported results were consistent across the vast majority of interviews, some level of validity could have been compromised as a result.

Another limitation to the study may be due to the reality of occasional poor recall on the part of the interviewees. Although most of the interviews were conducted during a period of time where the auto industry was in a state of transition, much of the anecdotes and examples given as evidence during the interviews were from personal testimony and experience. It is plausible, therefore, that some of the events involved did not occur exactly as recalled or stated by the interviewees.

Finally, garnering more information from additional data sources such as archival data, direct observations, and survey would provide more corroborating evidence to substantiate further more of the claims in the paper and provide further details regarding the modularity and mass customization phenomena occurring in the auto industry. As is, the bulk of anecdotal evidence gathered for this study is in the form of interview data.

VI. Conclusion

We have explored the impact modularity, as part of a viable mass customization strategy, is having on the U.S. auto industry at the beginning of the 21st Century. All apparent signs seem to indicate that mass customization and modularity, at least in terms of its thinking and conceptual benefits, is a serious change in strategy across the industry. How it is carried out is another story altogether. "… I think that modularity in its purest form can move the industry forward," states a former Manager involved with modularity programs at one of the American automakers. "… How it gets implemented is the real issue, not modularity per se."

Automakers and suppliers alike need to understand how mass customization and its use of modularity will affect their product development practices and supply chain structures. In recent years, modularity in the U.S. auto industry has been driven by cost reductions and the outsourcing of responsibility to the supply base. However, the existing infrastructure in the U.S. auto industry, ranging from tense labor relations to a lack of cost sharing, contains barriers that hinder the realization of modularity gains. Affecting firm relations and product design, modularity incorporates a multitude of socio-technical issues, something the U.S. auto industry is discovering very quickly. This suggests that the barriers to modularity themselves are socio-technical in nature, and cannot be easily discarded, overlooked, or overcome without the apparent impact on organizations and eventually the industry.

When companies that produce nonmodular products desire to move their products to a modular architecture, the change has to occur at the concept and design level, not merely the product assembly. The U.S. supply base seems to have enough technical and knowledge capability to produce modules on a large scale, a point repeated several times in many of our interviews both within OEMs and suppliers. And the lead suppliers in this supply base are already integrating their design capabilities through various mergers and acquisitions and contractual alliances. Where some integration capabilities have been lost via delayering and outsourcing policies, particular organizational set-ups are necessary to replace them [9].

Over decades, the Japanese OEMs and their keiretsu suppliers increased their information processing capabilities [46] which allowed them to work closely with suppliers and reduce their lead times, developing products much faster and at costs lower then their American counterparts [47]. American companies sought the cost benefits of efficient suppliers who take on engineering responsibility without the investment in an enabling infrastructure. But there is an inherent misfit between the coercive mechanisms used by American purchasing organizations and the great deal of responsibility being shifted to suppliers. The Japanese companies have evolved an effective hybrid of market and hierarchical control [38], but their U.S. counterparts are using a dysfunctional hybrid and are missing the control and enabling features that are apparent in the Japanese model. The Japanese OEMs are able to keep control by buying part of the supplier, but the American OEMs do not have the leverage provided by equity holdings in their suppliers, nor the history of effective partnering. So instead, they turn to market and cost pressures to get the suppliers to do what they want.

What the U.S. supplier management model does do well, however, is exert business control in a hierarchy. American OEMs are good at controlling suppliers through purchasing and market power and independent business units. They exert business control in a simulated hierarchy, so even though the suppliers are not owned by the OEM, the relationship is set up in a way such that the supplier is more strongly tied to the OEM than in the past traditional U.S. supplier management configuration. But unless the organization integration issues are addressed in the U.S. supplier management model, the U.S.'s failing will be on the technical integration side. They will get good cost reductions, but at the expense of systems integration that is necessary for the highest quality automobiles. The result is also financially weakened suppliers that cannot invest in the R&D required by this new business model.

There is a danger that the Big 3 approach to supplier management will become the dominant organizational design in America. Old ways are hard to change, and paradigms have a constraining effect. The U.S. supplier management model has broken technical and organizational systems and the problems will not go away just by coercive market forces. The underlying systems problem is still there, and it is this underlying problem that is more difficult and challenging to fix. Without fixing this, the promised benefits of mass customization and modularity will not be realized in the U.S. and may simply add to the Japanese competitive advantage.

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