

CIRJE-F-107

**Modularization in the Auto Industry:
Interlinked Multiple Hierarchies of
Product, Production, and Supplier Systems**

Akira Takeishi
Hitotsubashi University

Takahiro Fujimoto
University of Tokyo

March 2001

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INTERLINKED MULTIPLE HIERARCHIES OF
PRODUCT, PRODUCTION, AND SUPPLIER SYSTEMS**

First Draft: 2001/3/2

Akira Takeishi

Institute of Innovation Research, Hitotsubashi University
2-1 Naka, Kunitachi, Tokyo 186-8603, Japan
Phone:+81-(0)42-580-8425, Fax: +81-(0)42-580-8410
E-mail: takeishi@iir.hit-u.ac.jp

Takahiro Fujimoto

Faculty of Economics, University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
Phone:+81-(0)3-5841-5648, Fax: +81-(0)3-5841-5521
E-mail: fujimoto@e.u-tokyo.ac.jp

We would like to express our sincere appreciation to the interviewees and the participants of the supplier questionnaire survey for their collaboration. We also thank Seunghwan Ku for his assistance and contribution in data analysis. This research was partially assisted by a grant from Research for the Future Program of Japan Society for the Promotion of Science (JSPS) and a Grant-in-Aid for Scientific Research of JSPS.

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ABSTRACT

This paper analyzes the modularization in the world auto industry. The modularization in the industry has involved architectural changes in product, production, and supplier systems with each region (Japan, Europe and the U.S.A.) emphasizing different purposes and aspects. As an attempt to understand such multi-faceted, complex processes coherently, this paper proposes a conceptual framework that sees development / production activities as interlinked, multiple hierarchies of products, processes, and inter-firm boundaries. With this framework, drawing on case studies and questionnaire survey data, the paper examines the on-going processes of modularization in the industry. It is argued that tensions exist among the three hierarchies, and such tensions may lead to further changes in product, production and supplier-system architectures in the auto industry, in a dynamic and path-dependent manner.

1. INTRODUCTION

The concept of "modularization" has attracted increasing attention in the auto industry in the last few years. The meanings and purposes of modularization in this industry vary between regions and companies. There is no clear-cut definition of the term shared by the whole industry. Yet, there does exist a feature relatively common across various practices of modularization in the industry. It entails having larger units in subassembly and also often involves outsourcing these subassemblies to suppliers (as most frequently observed in the European auto industry).

This fact suggests that there are at least three facets in the phenomenon called "modularization": 1) "modularization in product architecture" (modularization in design) which has been discussed quite often in the field of the management of technology; 2) "modularization in production;" and 3) "modularization in inter-firm system" (outsourcing subsystems in larger units to outside suppliers). These three facets have often been mixed up, causing confusion in discussing modularization. While the European auto industry has been interested mainly in outsourcing, the Japanese has focused on modularization in production. Neither of them has addressed "modularization in product architecture." As we look further into the on-going practices in the auto industry, however, we can detect some changes that may lead to modularization in product architecture.

We observe in the auto industry such complicated, multi-faceted, and sometimes confusing processes of modularization. If we could present a single conceptual framework within which all trends in the industry can be analyzed somehow consistently, it would be a contribution to further our understanding of the concept of modularization. This is why this paper focuses on the auto industry. This paper also aims at probing into dynamic interactions and architectural changes between three systems — product, production, and inter-firm systems. Since modularization in the auto industry is still in a fluid, transitional stage at this moment, the industry provides us with a particularly interesting field where we can witness in real-time such dynamic interactions and architectural changes.

The next section of this paper lays out a conceptual framework that sees development and production activities for automobiles as multiple hierarchies of product, production, and inter-firm systems. This framework serves as the platform to be applied for the subsequent analysis. The following section describes the modularization in the auto industry. We investigate what is actually happening in the industry and the rationales behind these changes, while comparing the practices of

modularization in the Japanese, European, and the U.S. auto industries.¹ We then discuss how some changes in production and supplier systems would lead to changes in product architecture. The paper concludes by summarizing our analysis and discussing some implications for the future of the auto industry.

2. ANALYTICAL FRAMEWORK: DEVELOPMENT/PRODUCTION SYSTEMS FOR AUTOMOBILES AS MULTIPLE HIERARCHIES

Before investigating the actual practices of modularization being implemented in the auto industry, we would like to propose a conceptual framework as the premise for the analysis. One of this paper's purposes is to discuss the concepts of "modularization in product system," "modularization in production system," and "modularization in inter-firm system" within the same framework, and identify the differences and linkages between them. This framework is based on the concept of "multiple hierarchies." It sees development-production activities for automobiles as multiple, interlinked hierarchies. It contends that the hierarchies in product, production, and inter-firm systems make up one complex system where the three systems are related with each other (this framework is based on Fujimoto 1999).

Let us explain each of the three facets of modularization with this concept of "multiple hierarchies." First, "modularization in product" is defined in terms of the interrelation between the "Product Function Hierarchy" and the "Product Structure Hierarchy." We can illustrate such an interrelation with diagrams like those shown in Figure 1 (1) (Göepfert and Steinbrecher 1999, for example). The left diagram is a schematic representation of the so-called "integral" product. Since the elements making up the product function (the left triangle) are interrelated with those making up the product structure (the right triangle) in a complex manner, the designer of Subsystem [S1] has to take the following factors into account:

- 1) functional interdependence with the other subsystems (such as $s_1 \leftarrow f_1 \leftarrow s_2$, and $s_1 \leftarrow f_2 \leftarrow s_2$)
- 2) structural interdependence with the other subsystems (physical interference, for example, $s_1 \leftarrow s_2$)
- 3) interdependence with the design of the entire system (consistency with the design of

¹ This paper is based on the results of a series of interviews with automakers and component suppliers in Japan and other countries that was carried out from 1999 to 2000 as part of a research project on "Modularization and Outsourcing" at the MIT's International Motor Vehicle Program. We also conducted

the whole system, $s1 \leftarrow S1 \leftarrow S$)

- 4) interdependence between the sub-functions (such as $f1 \Leftrightarrow f2$, and $F1 \Leftrightarrow F2$).

“Modularization in product” decreases such interdependence between the concerned elements. It allows one-to-one correspondence between the subsystems and their functions, and enables, for example, the designer of Subsystem [S1] to focus solely on Sub-function [F1] and [S] (the structure of the product as a whole). The subsystem becomes a “module with a self-contained function,” which can be designed more autonomously. Remaining interdependence after modularization can further be reduced if the interfaces between the elements are simplified and standardized as much as possible.

We can illustrate “modularity in production” with the similar diagrams as shown in Figure 1 (2). It is comprised of the “Product Structure Hierarchy” (right triangle) and the “Product Process Hierarchy” (left). In order to simplify our explanation, among the whole manufacturing processes, we focus here only on assembly work in the “Product Process Hierarchy.” It is important to note that the “Product Structure Hierarchy” in this figure, as part of “Multiple Hierarchies of Product Structure and Production Processes,” and its counterpart in the previous “Multiple Hierarchies of Product Function and Product Structure” might have different hierarchical patterns. The former hierarchy is built up in pursuit of “functional independence” of each subsystem (i.e., the degree to which a function of the product is achieved by a single subsystem), while the latter is made up for “structural cohesiveness” (i.e., the degree to which a collection of parts can be physically handled as one unit). The latter hierarchy is intended to contribute to “structurally cohesive modules” which are easy to manage material handling and quality control. The difference between those two hierarchies can be understood by observing the parts list for the product design which is not same as the one for production management.

The left diagram represents non-modular production processes. Without any “structurally cohesive large modules,” the product is to be assembled from eight small modules ($s1$ to $s8$) at the same hierarchical level on one long main assembly line. On the contrary, in the right diagram, there are two structurally-cohesive modules “S1 and S2” on the right, and two subassembly lines to build them and one short main line for finished products on the left (remember the famous watchmaker story in Simon 1969). It can be said that the “Product Structure Hierarchy” with cohesive modules is translated into the “Product Process Hierarchy” with one main line and two subassembly lines.

a questionnaire survey of Japanese component suppliers.

Finally, let us explain “modularization in inter-firm system,” in which outside suppliers conduct and deliver subassemblies. The inter-firm division of labor in development and production (an automaker’s boundaries between in-house operations and outsourcing, or make-or-buy) can be defined for each of all steps of development-production activities from product function designing, product structure designing, production process designing, production preparation, to production. Here we focus on the division of labor in production processes which we often refer to when we talk about the make-or-buy decisions. That is to draw the boundaries of the involved companies over the production process hierarchy of the preceding diagram, as shown in Figure 1 (3). “Modularization in inter-firm system,” which has drawn increasing attention in the European auto industry, entails outsourcing subsystems in large units (cohesive modules) to suppliers. The left diagram is a schematic representation of production with a higher in-house ratio, in which small modules (s1 - s8) are delivered by outside suppliers. On the contrary, the right represents production based on a highly modular supplier system, in which large modules are assembled by outside suppliers on their subassembly lines, and are delivered and assembled into finished products on the main line of the automaker. We can apply the same illustration to describe the outsourcing of product designing (the so-called “approved drawings” or “black-box components”).

Overall, the three facets of modularization and their interrelations can be illustrated within the same framework of multiple hierarchies as shown in the three pairs of diagrams. Product engineers, process engineers, and purchasing managers must make decisions about the product and process hierarchies and the inter-firm boundaries, while securing close coordination between them. It is obvious that these three facets of modularization must not be mixed up. At the same time, it is also clear that these decisions are interrelated with each other. They are the processes of making decisions about interrelated hierarchies of product functions, product structure, and production processes. There is always a possibility of some inconsistency or conflict between the decisions. In a sense, the most critical challenge in modularization is how to avoid or overcome such inconsistency and conflict through coordination.

We have discussed the three decision-making processes from a rather static point of view thus far. Such decisions, however, in reality, are probably being made in a cumulative manner over time in most cases. We therefore have to take “path-dependency” into account — the outcome may depend on the specific sequence of decision-making.

The following section probes into the actual practices of “modularization” in both

Western and Japanese auto industries. Let us briefly summarize our analysis beforehand. Western automakers have a strong inclination toward “modularization in inter-firm system,” or outsourcing, which has stimulated “modularization in production.” One of their challenges is to cope with the inconsistency or conflict created between such “modularization in procurement/production” and “modularization in product architecture.” Japanese automakers, on the contrary, have focused on in-house “modularization in production” thus far and have been relatively quiet about aggressive outsourcing adopted by Western counterparts. Automakers in Japan instead seem to seek for “modularization in product architecture” facilitated by the need for the functionality and conformance quality of modules assembled on in-house subassembly lines. Since Western and Japanese auto industries have been following different paths in implementing modularization, their product architectures, production process hierarchies, and boundaries between in-house operations and outsourcing could be diverse, as they emerge.

3. MODULARIZATION IN THE WORLD AUTO INDUSTRY

3.1. European and U.S. Auto Industries

It is two German automakers, Volkswagen and Mercedes-Benz (presently Daimler-Chrysler), that geared up the auto industry's modularization in the mid-1990s. Their new assembly plants, which started production in 1996 and 1997, introduced modularization on a large scale, specifically at Volkswagen's plants in Resende (Brazil), Boleslav (Czech), and Mosel (former East Germany), and Mercedes-Benz's plants in Vance (U.S.) and Hambach (France).

These plants share two characteristics. One is that they have assembled cars from relatively large subassemblies. A car is a system made up of numerous components. There is a wide choice of managerial units at the intermediate stage in the process of putting them into a car. These plants have departed from the conventional way of assembling cars. At conventional plants, individual components — for example, instrument panels, gauges, and wire harnesses — one by one to a vehicle body on the final assembly line. Instead, at those new plants, these individual components are sub-assembled on a separate line, and then installed as a module into a body on the final assembly line. In the framework we discussed in the previous section, this is to redesign the hierarchy in production processes by setting a new intermediate layer to it (as

shown in the right diagram of Figure 1 (2)). Automakers in the world have divided cars into many parts in order to make development and production processes manageable. As some automakers have drastically redesigned the hierarchies in their development and production processes through modularization, others have also begun exploring new hierarchies.

The second characteristic shared by these plants is that they have let outside suppliers develop and assemble subassemblies. In the previous framework, this means to narrow the scope of in-house operations in the hierarchy of the inter-firm system (moving the inter-firm boundaries up to a higher hierarchical level), as shown in the right diagram of Figure 1 (3). MCC's plant in Hambach is a typical example of such outsourcing. MCC is a joint venture of Mercedes-Benz and SMH (a Swiss watch manufacturer), which assembles a two-seater small-sized car called "Smart." A group of suppliers called as "system partners" surround MCC's assembly plant. They build large modules such as cockpit modules, rear axle modules, and door modules, and deliver them directly to MCC's final assembly line. MCC even outsources body welding and painting, which traditionally automakers carry out in-house. Automakers in the United States have not yet become as aggressive in pursuing modularization as these German companies have. However, they have indicated their intention of letting their so-called "full-service" system suppliers handle larger sets of components in development and production.

There are three main reasons why Western automakers have been expanding the scope of outsourcing. First, they want to take advantage of the suppliers' lower labor costs. Second, they can cut investment costs and risk by giving more important responsibilities to the suppliers.² Third, these moves toward modularization have also been accelerated by their policy of reducing the number of the first-tier suppliers. This idea was originally taken from the Japanese automakers' approach (Clark and Fujimoto 1991, Cusumano and Takeishi 1991, Nishiguchi 1994). However, compared to their Japanese rivals, European manufacturers are already letting their suppliers handle larger modules. It seems that a strong sense of crisis that it has been difficult to make profits

² It is told, for example, that assembly plants actively outsourcing larger modules to suppliers can *gain pay back from their investment even on a relatively small scale of production. However, some interviewees at European and American automakers pointed out that the saving of labor and investment costs would not necessarily be very important advantages of modularization. Labor costs do not account for a large portion of total production costs in automobile manufacturing. Further, if suppliers' subassembly plants are adjacent to an automaker's final assembly plant, there exists a strong chance for the wage gap between the assembler and suppliers to be narrowed. It is also true that investment costs shared by suppliers would be reflected in the prices of their parts. For suppliers whose scale of business is relatively small, it is more likely that they have to pay higher capital costs than their customers.

from their car business underlies their aggressive outsourcing. In other words, they have been seeking outsourcing as part of an attempt to redesign “business architecture” (Fujimoto, Takeishi, and Aoshima 2001).

Responding to and promoting such demand from manufacturers, there have been a growing number of mergers and acquisitions among suppliers in the United States and Europe. They aim at establishing themselves as module suppliers and expanding business with major automakers by becoming qualified to manage the development and production of a larger set of components as a module.³

There are, however, some cases where module suppliers are assigned only to sub-assemble the components, each of which is still manufactured and designed by the incumbent suppliers. In these cases automakers still maintain control over the choice of suppliers for the individual components, as well as the management of their prices, quality, and design. Automakers have chosen to do so partly because they think that module suppliers are not capable of handling all aspects of the module. They are also concerned that extensive outsourcing to a limited number of suppliers may make the costs and technology of components unknown to themselves, reduce competitive pressure for suppliers, and thus weaken their own negotiation power. Nevertheless, such limited outsourcing probably only offers the limited advantage of cheap labor. It does not appeal to suppliers either because they are treated only as simple subcontractors with little added value while asked to invest lots of money and take risks. Automakers are still in the process of exploring where they should draw the boundaries in their development and production activities.

3.2. Japanese Auto Industry

Unlike the U.S. and European auto industries, the Japanese auto industry has shown few visible initiatives toward modularization. But when we looked closely into what Japanese companies are doing, through interviews and a questionnaire survey, we found out that they were dealing with the issue in a different style with different aims.

First, let us look at the results of our questionnaire survey.⁴ We conducted a questionnaire survey with 153 first-tier suppliers in February and March 1999. In this

³ See, for example, *Automotive News* (June 22, 1998). Lear Corporation is among such suppliers. Originally a seat manufacturer, the company acquired Ford’s seat production division in 1993. Since then the company has branched out into new component areas by buying 12 suppliers, and has grown into a leading supplier whose products cover entire car interiors, including instrument panels, door trims, roof trims, rearview mirrors, carpets, and air conditioners.

⁴ For the details of the questionnaire, see Fujimoto, Matsuo and Takeishi (1999).

survey, the term “modularization” was not used because there was no commonly shared definition of it. Instead, a number of questions about several important aspects of modularization were asked to capture recent changes in the industry. The respondents were asked the degree of changes over the last four years (a typical model changeover cycle) in 19 measures regarding design and production processes of their components.

A factor analysis of the responses has identified the following four factors: 1) component standardization, 2) shift to integral architecture, 3) functional independence/interface simplification, and 4) expansion of the subassembly scope. The results of this factor analysis suggest that it is difficult to generalize what is meant by modularization because it involves multiple dimensions.⁵

Table 1 shows the average scores of the answers. The biggest change over the last four years was “shift to integral architecture.” The functions assigned to individual parts had become more complex (Item 17), and the need for structural or functional coordination with other components had increased (Items 18 and 19). These changes were in an opposite direction to modularization. Note that we see signs of modularization in architecture in the increase of component sharing within each customer (automaker) (Items 6, 7, 13 and 14). Yet, the scope of component sharing was quite limited to among variations of a particular model, or at most, among different models of an automaker. There had been almost no attempts for component sharing across different automakers (Items 8 and 15). Further, there had been only little progress in the functional independence of components and the simplification of interfaces (Items 11, 12 and 16). There had been a very small number of cases where automakers had asked their suppliers to sub-assemble a larger set of components (Items 2, 3 and 4).

To sum up, the product architecture had become more integral, although some automakers had shown some interest in the use of standardized components and interfaces. On the other hand, there had been almost no progress in the type of modularization prevalent in the European and the U.S. auto industry, namely outsourcing of subassemblies in larger units to suppliers.

However, the above survey tells only about what component suppliers saw. If we look at what is happening inside automakers, a different picture appears. Figure 2 shows the results of our interviews (conducted from March to July, 1999) with eight Japanese automakers, about to what extent components around the instrument panels were sub-assembled before installed on the main assembly line for some of their

⁵ The factor analysis was done by Ku and is reported in Ku (2000).

models. It plots the number of component types sub-assembled for the model (vertical axis) and the year in which the model in question was introduced to the market (horizontal axis). The scores were all mean-centered for adjustment across automakers. We could see a positive correlation. The newer the model was, the wider the scope of the subassembly. In other words, there has been some progress in having subassemblies in larger units inside automobile assemblers.

Then, why have Japanese automakers promoted the in-house use of subassemblies? They have done so partly because they were stimulated by American and European rivals who have been actively adopting modularization. But some automakers are interested in modularization with a different perspective. It is based on their pursuit of “autonomous and complete” assembly lines.

Japanese automakers have traditionally built highly integral assembly lines, as epitomized by the famous Toyota's lines, for maximum efficiency. In order to eliminate any non-value-adding time, “muda,” they have combined different tasks flexibly. The improvement of the efficiency of each final assembly line as a whole has always been a number one priority. For the same reason, Japanese automakers have had their workers trained for multiple tasks and skills (“tanoko”). In short, the hierarchy shown in the left diagram of Figure 1 (2) has been most favored. The sequence of assembly processes and worker assignments have always been rearranged to achieve the maximum efficiency under changing situations. The introduction of a subassembly line, which involves the isolation of a particular set of tasks from the main line, as shown in the left diagram, hinders flexible task rearrangement for optimizing the whole system. For example, those workers assigned to the subassembly line are not to help their colleagues at the main line even when a problem occurs. On this account, they have traditionally been reluctant to have subassembly lines in their plants. But they have begun changing their views since the early 1990s for several reasons.

First, automakers have placed a greater importance on their employees' satisfaction from their work. This change originated in the serious shortage of workers during the bubble economy (Fujimoto and Takeishi 1994). It has also been influenced by the necessity of dealing with the growing number of female and elderly workers. The adoption of subassembly lines improves the workers' satisfaction in two respects. First, working for a subassembly line allows workers to maintain a comfortable working position (better ergonomics). Suppose your job is to attach various components around the instrument panel. If you work on a main line, you may have to stand in a torturous position, leaning over the panel in the car. By contrast, if you work on a subassembly line, you can maintain a relatively comfortable working position, standing while

attaching all the components to the panel. In addition, it is considered that handling a functionally related set of tasks helps you understand the significance of your work. This would motivate and satisfy workers.

Second, they have placed a greater importance on self-contained quality control system. According to this idea, the quality of each subassembly is inspected upon its completion, not on the final line as part of a finished product, in order to find defects at the earliest stage possible. The adoption of self-contained quality control has facilitated the adoption of subassemblies to be inspected upon completion. This is closely related to the significance of work mentioned above. If you can check the quality of a subassembly you have just completed, you can gain a sense of your work's significance and accomplishment.

With an increasing emphasis on workers' satisfaction and self-contained quality control, Japanese automakers have been replacing their conventional integral lines with new self-contained lines, and thus been adopting more and more subassemblies.⁶ However, they have been reluctant to outsource the subassemblies to outside suppliers, as confirmed in the results of the previous questionnaire survey as well as our interviews with automakers. This is a big difference compared to the European auto industry where modularization often proceeds with outsourcing.⁷

There are some reasons for this reluctance. First, the cost advantage in outsourcing modules is not so great in Japan because the wage gap between automakers and the first-tier suppliers is narrow compared to Western counterparts. Second, in order to have outsourced subassemblies delivered in sequence to the main line on short lead times, the suppliers' shops should be located within a very short distance from the assembling plants. Yet investment opportunities for building such new facilities are currently quite limited in Japan. Even if this is possible, automakers are concerned that each plant might rely too much on the particular suppliers selected, and thus its competitive pressure toward them might be reduced. Third, automakers have been doubtful about the capability of suppliers to handle a larger scope of tasks since Japanese suppliers have long specialized in the development and production of individual functional components. It is also true that Japanese automakers have a dislike for losing knowledge about the technology and costs of any parts involved. The absence of those component suppliers who have proactively had mergers and

⁶ Some automakers have also tried to divide their main lines into some self-contained sub-blocks. For this new assembly system, see Fujimoto 1999.

⁷ Some European automakers, however, put emphasis on in-house production. For example, Audi, a company of the Volkswagen Group, focuses on in-house production at its Ingolstadt Plant, Germany. It outsourced some subassemblies to outside suppliers, but plans to have them back to in-house operations.

acquisitions in order to develop and produce larger modules as emerging in the United States and Europe, has also kept Japanese automakers primarily focused on in-house subassemblies.

4. REDEFINING PRODUCT ARCHITECTURE

As we have discussed thus far, the modularization in the auto industry has centered upon the redefinition of hierarchies in production system and inter-firm system. The former entails the expanded use of subassemblies, the change common in the Japanese, European and U.S. auto industries. The latter involves the expanded use of outsourcing, which has been prevalent in Europe and the U.S., but inconspicuous in Japan.

The redefinition of hierarchies in production and inter-firm systems is essentially different from modularization in product system (as shown in Figure (1)). In the first place, cars are usually categorized as relatively integral products in terms of product architecture (Fujimoto 2001), and thus are difficult to be modularized further. But if we probe into what is happening in the industry, we observe some movements in which the redefinition of hierarchies in production and inter-firm systems may lead to modularization in product architecture.

Among such movements is the redesigning of the components necessitated by the adoption of subassemblies, which has been addressed by Japanese automakers. The use of subassemblies has some disadvantages. A subassembly built from many components is difficult to handle because of its size and weight. Such a subassembly is also difficult to be fitted perfectly onto other subassemblies or the body. Accuracy in assembling work is difficult to achieve with subassemblies compared to that of smaller, individual components. If some additional parts or fixtures are needed only to ensure ease of handling and accuracy, it would end up with an unacceptable increase in costs and weight. Furthermore, unless the assignment of functions to some components is redefined, it may be often impossible to check the quality of a sub-assembled module.⁸

In order to solve these problems brought up by modularization, Japanese automakers have put great emphasis on redesigning the components within a subassembly module. Such efforts include the integration of some components into

⁸ It is also true that Japanese-style production, which often uses mixed-model assembly lines (in which different models are assembled on the same line), prevents automakers from adopting subassemblies. Suppose you decided to use subassemblies for the production of a certain model, *then assembly work on the main line would be quite uneven between different models, making the operation inefficient. Note, however, that this problem will be solved over time.

others for reduced cost and weight, and the re-assignment of functions to realize the self-contained quality control (for example, making the functions of an instrument panel module more independent so that the quality of its electric system can be tested independently). These attempts are nothing but the redefinition of product architecture. The integration of some components into others involves making the product architecture of certain sets of components more integral. Making the function of a set of components more independent entails the modularization of the set.

Such attempts to redesign have been triggered by the redefinition of the hierarchies in production systems, and may lead to the redefinition of organizational boundaries (following the path: “Modularization in Production System” → “Modularization in Product Architecture” → “Modularization in Inter-firm System”) (See Figure 3). According to Fujimoto and Ge (2001), the “approved drawings” (or “black-box components”) are more likely to be adopted for certain parts for which the responsibilities for quality control can be clearly defined. In other words, such parts can be outsourced because the functions assigned to them can be managed by outside suppliers as independent, self-contained units. If the redefinition of product architecture allows us to redefine the scope of quality control responsibilities in larger units, development and production within that scope could be outsourced more easily to outside suppliers. As a result, outsourcing of development and production would be further promoted.

Some Western automakers include “a testable set of components” as the important conditions for modularization. This suggests that the assignment of independent (testable) functions has been treated as an important requirement for outsourcing. This implies the sequence that “Modularization in Inter-firm and Production Systems” facilitates “Modularization in Product Architecture” (Figure 3).

Probably the most outstanding example of products developed in this manner is “Smart” being manufactured in the aforementioned MCC plant. This car is comprised of a highly unique body frame called a TRIDION cell and plastic body panels. Unlike the integral architecture of ordinary passenger cars with a mono-cock body, Smart’s product architecture was designed to be built from modules. Bosch, one of the largest component suppliers in the world, once pointed out that one of the requirements for successful modular production was to design a car optimized for modules, and cited Smart as an example. The development of such a car can be described as a process in which the division of labor with outside suppliers expedites the redefinition of the relationships between functions and structures to define explicit conditions for contract and evaluation measures, and, as a result, the architecture of the product becomes

modularized.

Product architecture would be redefined in the process of modularization in both the Japanese and European auto industries. But the difference in the paths they have followed might make their new architecture different in nature (Figure 3). In Japan, the redefinition of product architecture has been addressed under the leadership of automakers in cooperation with multiple suppliers.⁹ In Europe, automakers have often outsourced a large set of components to a single supplier (who has become a module supplier through mergers and acquisitions), and the redefinition of product architecture is pursued according to the inter-firm boundaries in this relationship. If knowledge of the entire product is the most important requirement for the redefinition of its architecture, the automaker-led style of the Japanese auto industry might have an advantage. On the other hand, the supplier-led redefinition of architecture in Europe and the United States might bring about more innovative architecture that no assemblers could have ever recognized.

It should be noted that modularization in this industry is basically adopted for individual models. Even Western automakers use particular modules for particular plants or models. There has been no case of adopting the same modules across different models or plants. The same applies to subassemblies and design rationalization in the Japanese auto industry. In this sense, the modularization in the auto industry is essentially different from open modularization observed in personal computers, bicycles, and stereo component systems. If an automaker outsources design tasks in very large units to one particular supplier, the free hand given to the supplier might allow it to pursue the component sharing and standardization to a certain extent. However, since the optimization of each model for better product integrity is of great importance in the industry, we have not seen any extensive attempt toward the commonalization and standardization of interfaces across different automakers.¹⁰

⁹ Since suppliers have extensive knowledge of individual components, their cooperation is indispensable for the development of any modules, even if its subassembly is done in-house by an automaker. There is a unique approach called "kyogyo" in the Japanese auto industry in which a number of suppliers work together to develop sets of components in larger units, under the leadership of an automaker. For examples of design streamlining through "kyogyo," see "Nikkei Mechanical," January 1999.

¹⁰ The auto industry's resistance to standardization has a long history. In 1910, the Society of Automotive Engineers (SAE) proposed the standardization of parts across the industry. It wanted to make assembly work more efficient by ensuring compatibility between different parts of different automakers. While relatively small-sized automakers supported the proposal, it did not become a reality due to resistance from major assemblers such as Ford and GM. They did not want to lose the strong position they had established (economy of scale) and stuck to their own standards (Langlois and Robertson 1992).

5. DISCUSSION: DYNAMICS OF MODULARIZATION IN THE AUTO INDUSTRY

Modularization in the auto industry is still in the trial and error stage. The industry began addressing the issue only several years ago. The contexts and purposes of modularization vary across regions and companies. So it is still quite uncertain and unpredictable how it will be evolved and what impacts it will have. Our argument is therefore no more than speculation. Yet, it would be safe to say that on-going processes concerning modularization provide us with some interesting cases to explore the dynamics surrounding architectural changes.

What lies in the center of the dynamics is interactions between production system, inter-firm system, and product architecture. Changes in the hierarchies in production system and/or inter-firm system cause tension in their relationships with product architecture, and thus encourage the redefinition of product architecture.

Baldwin and Clark (2000) pointed out that the issue of modularization involves “modularity in design,” “modularity in use,” and “modularity in production” (though their discussion primarily focused on “modularity in design”). Sako and Murray (1999) argued that each of these has its own optimal architecture, and thus well-balanced relationships among them should be maintained in the process of modularization. This suggests that these three aspects of modularization are correlated with each other and close coordination among them is necessary. Sako and Murray further pointed out that coordination has to be secured between product architecture and organizational architecture (intra-firm and inter-firm organizations) as well. Echoing with their argument, this paper also suggests that changes in inter-firm system might lead to changes in product architecture. It is well known that modularization in product architecture sometimes changes the structure of the division of labor in the industry (from a vertical industry structure to a horizontal industry structure) (Fine 1998). This paper suggests that the relationship between product architecture and inter-firm system is two-way—— not only the former influences the latter, but also the latter has some impact on the former.

As argued in Section 2 on the analytical framework, the hierarchies in product system, namely hierarchies in product structure and product function, correspond to those in production system and inter-firm system. Hierarchical structure of a complex system is formed as a method to rationalize the division of labor (Simon 1969). Each of product, production, and inter-firm systems has its own logic of the division of labor. Hierarchies in production system and inter-firm system change in their own contexts

(for example, the improvement of workers' satisfaction, the utilization of the wage gap between different companies, the reallocation of risk and investment burden, and so on). And such changes in production and inter-firm systems would demand changes in product architecture. Conditions within design activities are not a sole factor for changes in product architecture. European automakers, for example, are exploring new architectures across inter-firm, production, and product systems in search of a more profitable business model (though the outcomes are still yet to be seen).

Modularization in the auto industry seems to proceed with hierarchical changes in each of product, production, and inter-firm systems in its own context and with its own logic, and at the same time evolve through dynamic interactions among these multiple systems of hierarchies. If this is the case, the key to successful modularization for automakers probably lies in close cooperation and coordination between their development, production and purchasing functions, as well as with their suppliers.

Given different business environments, different capabilities and strategies, and different paths toward modularization, we might see the co-existence of various patterns of modularization in the world auto industry. Also, there could be a scenario for multiple patterns of modularization being used for different product lines and market segments. Or, if any particular pattern would command an outstanding competitive leadership, the entire industry may be converged into that pattern of modularization. The future of modularization depends on which pattern would allow automakers to design and produce cars with greatest value s for consumers.

The future of technological innovations in the medium or long term is also important. The urgent need to protect the environment has accelerated the competition for a new power source (such as hybrid engines and fuel cells) to replace the conventional internal-combustion engines. With rapidly advancing information and communication technologies, the development of ITS (Intelligent Transportation System) has also been progressing. The growing importance of information technologies in vehicles has made the role of software much more important, and thus may facilitate a kind of modularization through the separation of hardware and software. When those new technologies are put into practical use, the architecture of cars will have to be totally redesigned and such changes will inevitably influence production and inter-firm systems as well. It is anticipated, under such circumstances, new architectures (for product, production and inter-firm systems) of the auto industry will be established through dynamic interactions between on-going attempts of modularization and emerging new technological innovations.

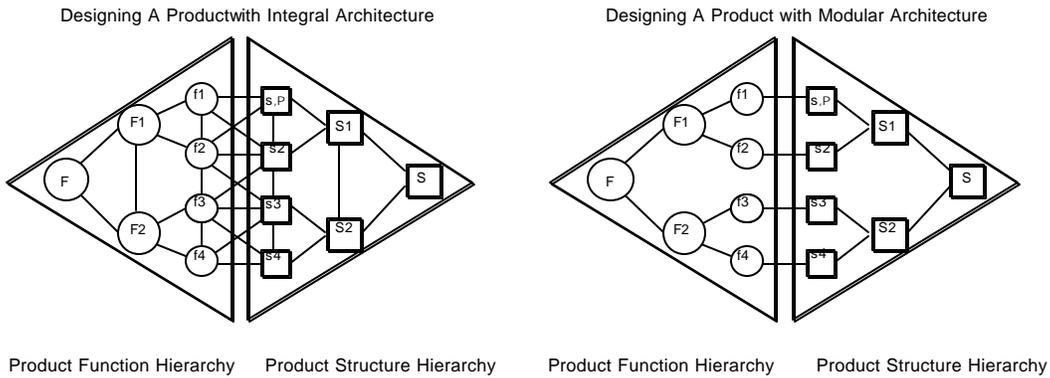
REFERENCES

- Baldwin, Carliss Y. and Kim B. Clark (2000). *Design Rules: The Power of Modularity*. Cambridge, MA: MIT Press.
- Clark, Kim B. and Takahiro Fujimoto (1991). *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry*. Boston, MA: Harvard Business School Press.
- Cusumano, Michael A. and Akira Takeishi (1991). "Supplier Relations and Management: A Survey of Japanese, Japanese-Transplant, and U.S. Auto Plants." *Strategic Management Journal* 12 (8):563-588.
- Fine, Charles H. (1998). *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*. Reading, MA: Peruseus Books.
- Fujimoto, Takahiro (1999). *The Evolution of a Manufacturing System at Toyota*. New York: Oxford University Press
- Fujimoto, Takahiro (2001). "Akitekucha no Sangyoron" [Industry Analysis by Architecture]. In Takahiro Fujimoto, Akira Takeishi, and Yaichi Aoshima (eds.), *Bijinesu Akitekucha: Seihin, Soshiki, Purosesu no Senryakuteki Sekkei [Business Architecture: Strategic Design of Products, Organizations, and Processes]* Tokyo: Yuhikaku.
- Fujimoto, Takahiro and Ge Dong Sheng (2001). "Jidosha Buhin no Akitekuchateki Tokusei to Torihiki Hoshiki no Sentaku [Architectural Characteristics of Auto Components and Choices of Transaction Systems]." In Takahiro Fujimoto, Akira Takeishi and Yaichi Aoshima (eds.), *Bijinesu Akitekucha: Seihin, Soshiki, Purosesu no Senryakuteki Sekkei [Business Architecture: Strategic Design of Products, Organizations, and Processes]* Tokyo: Yuhikaku.
- Fujimoto, Takahiro, Takashi Matsuo, and Akira Takeishi (1999). "Jidosha Buhin Torihiki Patan no Hatten to Henyo: Wagakuni Ichiji Buhin Meka heno Anketo Chosa Kekka wo Chushin ni [Development and Transformation of Car Component Transaction Patterns: Results from a Questionnaire Survey with Japanese First-tier Suppliers]." Discussion Paper CIRJE-J-17, Faculty of Economics, University of Tokyo.
- Fujimoto, Takahiro and Akira Takeishi (1994). *Jidosha Sangyo 21-seiki heno Shinario [The Automobile Industry: A Scenario towards the 21st Century]* Tokyo: Seisansei Shuppan.
- Fujimoto, Takahiro, Akira Takeishi, and Yaichi Aoshima (eds.) (2001). *Bijinesu Akitekucha: Seihin, Soshiki, Purosesu no Senryakuteki Sekkei [Business Architecture: Strategic Design of Products, Organizations, and Processes]* Tokyo: Yuhikaku.
- Göpfert, Jan, and Mitchel Steinbrecher (1999). "Modular Product Development: Managing Technical and Organizational Interdependencies." Mimeo.
- Ku, Seunghwan (2000). "Nihon Jidosha Sangyo ni Okeru Mojuraka no Doko to Kigyokaneki ni Kansuru Kenkyu: Mojuraka ni Taisuru Hihanteki Kento wo Chushinni" [A Study of Modularization and Inter-firm Relationships in the Japanese Automobile Industry: A Critical Examination of Modularization]. Unpublished Master's Thesis, Faculty of Economics, University of Tokyo.
- Langlois, Richard N. and Paul L. Robertson (1992). "Networks and Innovation in a Modular System: Lessons from the Microcomputer and Stereo Component Industries." *Research Policy* 21: 297-313.
- Nishiguchi, Toshihiro (1994). *Strategic Industrial Sourcing: The Japanese Advantage*. New York, NY: Oxford University Press.
- Sako, Mari and Fiona Murray (1999). "Modules in Design, Production, and Use: Implications for the Global Automobile Industry." Paper submitted to MIT IMVP Annual Sponsors Meeting, Cambridge, MA.

Simon, H.A. (1996 (1969)). *The Science of the Artificial*. Third ed., Cambridge, MA:
MIT Press.

Figure 1 Multiple Hierarchies of Product, Production and Supply Systems

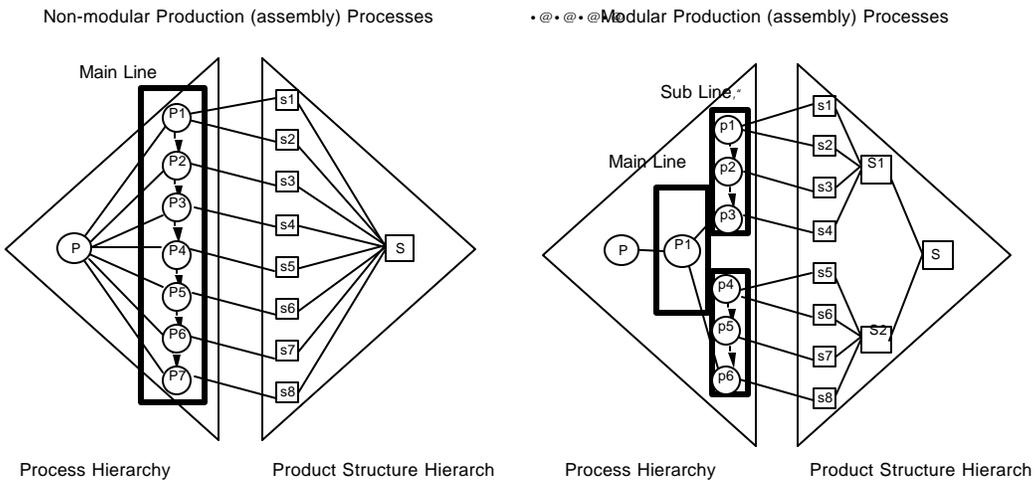
(1) Modularization in Product
(Multiple Hierarchies of Product Function and Product Structure)



Legends: F = Product Function as a Whole, S = Product Structure as a Whole
 F1, F2=Sub-functions of the Product, f1 - f4 = Sub-sub-functions of the Product
 S1, S2 = Large Modules, s1 - s4 = Small Modules
 ----- = connection

* In order to simplify the diagram, the connection between F and S, and the same between F1, F2, S1 and S2 are omitted.

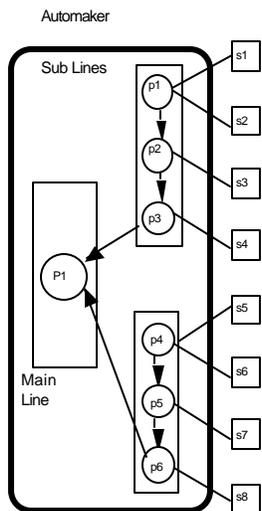
(2) Modularization in Production
(Multiple Hierarchies of Product Structure and Production Processes)



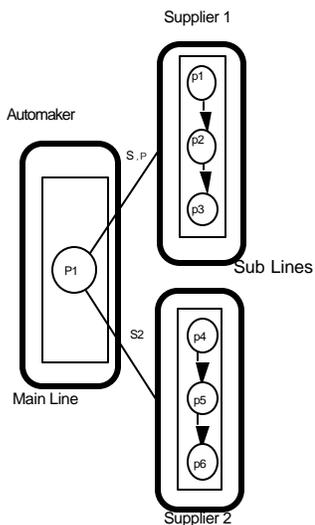
Legends: P = Production Process as a whole, S = Product Structure as a Whole,
 P1, P2= Main Line Processes, p1-p2= Sub-line processes, S1, S2 = Large Modules
 ----- connection in terms of product designing or process designing s1-s4= Small modules
 ->@ = Process Flow
 [] = Assembly Line

(3) Modularization in Supplier Systems
 (Multiple Hierarchies of Production Process and Inter-Firm Systems)

Non-modular Supplier System



Modular Supplier System



Legends: P = Production (assembly) Process as a Whole, S1, S2 = Large Modules, s1 to s4 = Small Modules
 •••••P1= Main Line Process, p1 to p2 = Sub-line Processes

- = Process Flow
- = Inter-firm Relationship
- ▭ = Assembly Line
- ▭ (with thick border) = Inter-firm Division of Labor

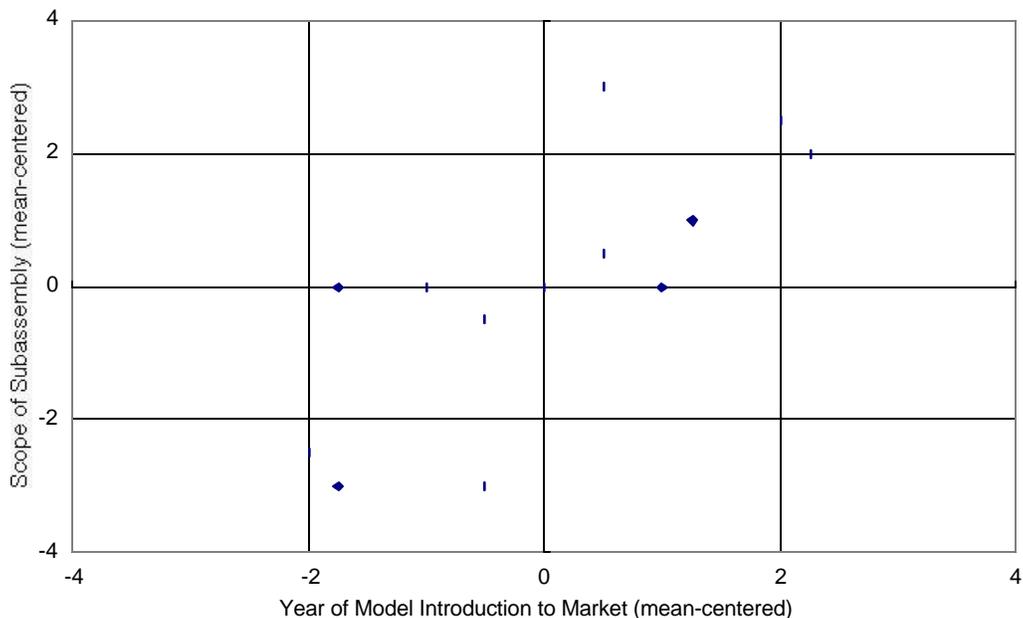
**Table 1 Recent Changes of Component Development and Production
In the Japanese Auto Industry
(Results of a Questionnaire Survey with First-tier Suppliers)**

	Standardization of Component Design Within an Automaker	Architectural Integrity	Functional Independence/ Interface Rationalization	Expansion in Sub-Assembly Scope	Score
1 Size of the component reduced with the same basic structure.			• δ		0.31
2 Number of parts making up the component increased.				• δ	0.02
3 Number of assembly process steps for the component increased.				• δ	0.09
4 Component has been incorporated into an other assembly component					0.07
5 Process steps and costs to assemble the component decreased with the adoption of integrally-molded parts.					0.47
6 Component design was shared by different models of the same automaker.	• δ				0.44
7 Component design was shared between different variations of the same model.	• δ				0.57
8 Component design was standardized across different automakers.					0.19
9 Component design was shared by the current and earlier models.					-0.11
10 Number of variations within a vehicle model decreased.					0.19
11 Number of interfaces (such as contact points) with other components decreased.			• δ		0.13
12 Designs of interfaces (such as contact points) with other components were simplified.			• δ		0.19
13 Designs of interfaces (such as contact points) were standardized within a model.	• δ				0.28
14 Designs of interfaces (such as contact points) were standardized between different variations of a model.	• δ				0.40
15 Designs of interfaces (such as contact points) were standardized across different automakers.					0.09
16 Function of the model became more self-contained (independent).			• δ		0.11
17 Function of the model became more complex (with more functions required).		• δ			0.62
18 Need for functional coordination with other components increased		• δ			0.62
19 Need for structural coordination with other components (such as checking matching and interference.		• δ			0.63
Average Score	0.42	0.62	0.19	0.05	0.28

Note: This table is based on the results of a questionnaire survey with 153 Japanese first-tier suppliers, which was conducted in February and March 1999, in Japan. The respondents answered the degree of changes in each item. Scores were: "changed" = 2, "no changes" = 0, "changed adversely" = -2. Columns are the four factors identified by a factor analysis. δ indicates that the item had a strong correlation with the corresponding factor. The scores in the bottom rows are the average scores for the items with a strong correlation with the factor. See Fujimoto, Matsuo, and Takeishi (1998) for the details of the questionnaire survey, and Ku (2000) for the results of the factor analysis.

Source: Questionnaire Survey with First-tier Suppliers in Japan (1999)

Figure 2 Changes in Scope of Subassembly Around Instrument Panels at Japanese Automakers' Assembly Plants



This figure plots the relationship between the number of components sub-assembled around the instrument panels, and the year in which the model in question was introduced to market.

The scores are all mean-centered within each automaker. For the year of market introduction, the score measures a difference between the year in which the model in question was launched and the average year in which the automaker's sample models were launched. The higher the score, the newer the model is among the automaker's models in the sample. For the scope of subassembly, the score measures a difference between the number of components sub-assembled for the model in question and the average number of components sub-assembled for the automaker's sample models. The higher the score, the larger the scope of subassembly is among the automaker's models in the sample.

Components examined for subassembly include: instrument panels, gauges, meter panels, glove compartments, wire harnesses, air conditioner switches, air conditioner units, air conditioner blowers, air conditioner ducts, air vents, audio systems, navigation systems, steering shafts, steering columns, steering switches, ignitions, column shifts, air bags (for drivers), air bags (for passengers), cup holders, ashtrays, pedals, and cross members (23 components).

Source: Interviews with Eight Japanese Automakers (conducted in spring and summer, 1999).

Figure 3 Dynamics of Modularization in the Auto Industry

