Modularization in Black-Box Design:
Implications for Supplier-Buyer Partnerships

Juliana Hsuan

Copenhagen Business School
Department of Industrial Economics and Strategy
Nansensgade 19, 2
DK-1366 Copenhagen K.
Denmark
Tel: +45 3815 2941
Fax: +45 3815 2540
Email: jh.ivs@cbs.dk

Helsinki School of Economics and Business Administration
Department of Logistics
Runeberginkatu 22-24
FIN-00100 Helsinki
Finland
Tel: +358 9 4313 8329
Fax: +358 9 4313 8669
Email: Juliana.Hsuan@kyyppari.hkkk.fi

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Abstract

New business practices are forcing high-tech firms to reconsider their strategic thinking in R&D and supply chain management. How do these firms manage differing new product development strategies to facilitate collaboration with suppliers and customers? This paper examines the effects of modularization in black-box design and subsequent impacts on supplier-buyer partnerships by evaluating the opportunity for modularization at four different levels: component, module, sub-system, and system. The scope of modularization sensitivity is assessed in terms of the product’s architecture, interface compatibility effects, component customization, value inputs, and supplier-buyer interdependence. An example of windshield wipers controller for Chrysler Jeeps illustrates that, higher opportunities for modularization in black-box design can be attained through a more collaborative form of supplier-buyer partnerships.

Keywords: Black-box design; modularization; new product development; supplier-buyer partnerships

1. Introduction

The globalization of markets in addition to the increasing pressures from aggressive foreign competitors are forcing high-tech firms[1] to reconsider their strategic thinking in research and development (R&D)[2] and supply chain management. Many firms are coping with this challenge through strategic partnerships and alliances including outsourcing of product development and manufacturing activities. It has been estimated that the annual growth rate in the number of alliances is around 25%. Surprisingly, approximately 60-70% of all alliances fail (Bruner and Speckman, 1998). A recent study published by KPMG reported that 70% of the failure rate is caused by problems attributed to the relationship shared with the partners such as commitment, complementarity, culture, trust, and chemistry (Duysters et al., 1998). So how are firms coping with these challenges? What kinds of product design strategies should be pursued to facilitate the supplier-buyer relationships?

A great majority of literature on partnerships and alliances focus on the social and strategic issues as to understand why firms form alliances with what types of alliances. The term supplier-buyer partnerships have been referred to as collaborative partnerships, collaborative strategic alliances, or partnership sourcing (Baily et al., 1998:160-161; Parker and Hartley, 1997; Kamath and Liker, 1994). Chiesa and Manzini (1998) and Gulati (1998), for example, provide comprehensive discussions on organizational modes for technical collaboration, and alliances and networks respectively. Many firms are delegating more design and manufacturing responsibilities to their suppliers in order to gain flexibility and cost benefits. Although most practitioners and academics agree that strategic analysis of a firm and its products should be assessed concurrently, very little is written about specific strategies in R&D and their impact on the supply chain management, or vice-versa. Recently, a couple of concepts have been gaining increasing attention among academic research in bringing R&D management a step closer to supply chain management. For example, *mass customization* (Gilmore and Pine II, 1997; Pine II, 1993) emphasizes the need to provide outstanding service to customers in providing products that meet customers' unique needs at a low cost. The aim is to manufacture components and modules with more variety and customization through flexibility and quick responsiveness. Similarly, *postponement* brings a high-tech firm closer to its customers by improving a firm's logistics productivity. According to Bowersox (1982), postponement is defined as a 'dimension of the sequence, timing and scale of operation necessary to support differentiated marketing. At the root of postponement is the economic principle of substitutability. In brief the two notions of postponement are: (1) postpone changes in form and identity to the latest possible point in the

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[1] High-tech firms in this paper refer to firms engaged in state-of-the-art technology, characterized by rapid rate of change in their products and technologies. Some analysts classify firms in high technology industry as those that spend more than 3 percent of sales on R&D (Maidique and Hayes, 1985).

[2] In industries, there are no clear distinction between *research* and *development*. The purpose of research is to develop new knowledge, and the purpose of development is to apply scientific or engineering knowledge, to expand it, to connect the knowledge in one field. In general, development also seeks to move product or process concept through a series of stages to prove, refine, and ready them for commercial application (Roussel et al., 1991). Thus, the process of innovation can be represented as a set of research and development activities.

distribution system, and (2) postpone changes in inventory location to the latest possible point in time.'

In this paper, the concept of *modularization* in black-box design is described. Modularization can be a crucial factor for a firm engaged in mass-customization and postponement strategies. Because modularization is often supported by the use of standard components, customization is possible through mix-and-match of these components. It can significantly reduce and standardize manufacturing assemblies and processes, subsequently changing the nature of collaboration a firm shares with its suppliers and customers (Hsuan, 1998a; Hsuan, 1998b). The nature of supplier-buyer relationships range from 'durable-arm's length relationships' to 'strategic partnerships.' The 'durable arm's-length' model of purchasing strategy was mainly practiced in the U.S. during the 1980s, where buyers kept suppliers at "arms-length" to avoid dependence on suppliers and to maximize bargaining power. The durable arm's length model fits best for low value, non-strategic inputs that are not related to the buying firm's core competence or that play a significant role in differentiating the buying firm's products. For example, resistors, capacitors, nuts and bolts are considered standardized and stand alone components. The management of such components does not require high coordination because the supplier-buyer interdependence tends to be minimal. It has been stated that in order to increase supplier-buyer interdependence, the buyer should increase its purchases from a single supplier (Dyer et al., 1998). Competition will always exist when more than one supplier is involved, and *modularization* has a critical role in the global trend in reducing the number of suppliers. The 'strategic partnership' model, on the other hand, is often referred to as the Japanese-style partnership (JSP) (Dyer and Ouchi, 1993). One reason is that the Japanese automakers work closely with their customers and affiliated suppliers[3].

The paper is organized as follows. Firstly, some definitions and terms associated with modularization are explained followed by the analysis of modularization in four different stages. Secondly, some issues related to in-house versus outsourcing of new development projects are discussed including the role of modular innovation in black-box design. Then, the characteristic curves of modularization are introduced. Thirdly, the contrasting characteristics of 'durable arm's-length relationships' with 'strategic partnerships' are portrayed and analyzed with the characteristic curves. Finally, an example of Chrysler Jeep's windshield wipers controller is illustrated.

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[3] The contrasting approaches between American and Japanese ways of handling supplier-buyer management practices in the automotive industry have been well studied (Dyer et al., 1998; Lamming, 1993; Dyer and Ouchi, 1993; Womack et al., 1990; Altshuler et al., 1986; Cusumano, 1985).

2. Background on Modularization

Although *modularization* is not a new concept, it is emerging as a strategic process in R&D and supply chain management[4]. This complex process is gaining more credibility in the academic world. The process of modularization often relates to *modularity* (Sanchez and Mahoney, 1996; Baldwin and Clark, 1997), *modular innovation* (Henderson and Clark, 1990; Christensen and Rosenbloom, 1995), *modular system* (Langlois and Robertson, 1992; Baldwin and Clark, 1997), *modular components* and *modular product design* (Sanchez and Mahoney, 1996), *modular product architecture* (Ulrich and Eppinger, 1995; Sanchez and Mahoney, 1996; Lundqvist et al., 1996), and *remodularization* (Lundqvist et al., 1996). Table 1 lists the definition of these terms.

Table 1. Definition of Modularization Terms.

Definitions of Modularization Terms	
Modularity	▪ A special form of design which intentionally creates a high degree of independence or 'loose coupling' between components designs by standardizing component interface specifications (Sanchez and Mahoney, 1996) ▪ The building of a complex product or process from smaller subsystems that can be designed independently yet function together as a whole. It is a strategy for organizing complex products and processes efficiently (Baldwin and Clark, 1997)
Modular System	▪ A network of subproducts, from which a product that had been treated as an entity, that consumers can arrange into various combinations according to their personal preferences (Langlois and Robertson, 1992) ▪ A system composed of units (or modules) that are designed independently but still function as an integrated whole (Baldwin and Clark, 1997)
Modular Innovation	▪ It denotes the introduction of new component technology inserted within an essentially unchanged product architecture (Christensen and Rosenbloom, 1995) ▪ An innovation that changes only the relationships between core design concepts of a technology. It is an innovation that changes a core design concept without changing the product's architecture (Henderson and Clark, 1990)
Modular	▪ Components whose interface characteristics are within the range of variation allowed by a modular product architecture (Sanchez and

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[4] The widespread adoption of modular designs is best known in the computer industry in which the rate of innovation has been phenomenal. Other successful stories of modularization include Sony's Walkman, Swatch watches, GE's dishwashers, and software designs (Sanchez and Mahoney, 1996).

Definitions of Modularization Terms	
Components	Mahoney, 1996)
Modular Product Design	▪ The standardized interfaces between components are specified to allow for a range of variations in components to be substituted into a product architecture (Sanchez and Mahoney, 1996)
Modular Product Architecture	▪ A special form of product design that uses standardized interfaces between components to create a flexible product architecture (Sanchez and Mahoney, 1996) ▪ An architecture in which each physical 'chunk' implements a specific set of functional elements and has well-defined interactions between the 'chunks' (Ulrich and Eppinger, 1995)
Remodularization	▪ The redefinition of the modular architecture or architectural innovation of the product in question. It mainly includes the reconfiguration of product subsystems and not necessarily changes in functionality or the technical performance of components (Lundqvist et al., 1996)

2.1. Levels of Modularization

The process of modularization in new product development can take place at many different levels: Component Level, Module Level, Sub-System Level, and System Level. Figure 1 illustrates different levels of modularization in automobiles.

***Component Level*:** This is considered the lowest level of modularization, represented by standard, off-the-shelf parts such as resistors, capacitors, connectors, epoxies, and so on. For electrical systems, they are usually the printed circuit board (PCB) level components, mostly listed in catalogs with low unit prices varying according with the volume purchased. Specifications of these parts are generally well defined and are accepted as industry standards. Parts suppliers offer a variety of products to many industries, often serving no particular industry. For example, semiconductors, resistors, and capacitors (each produced by different suppliers) are found in medical equipment, automotive electronics, consumer electronics, etc. The supplier-buyer partnership at this level often portrays the characteristics of a durable arm's length relationship: low component customization, low value inputs, and low degree of supplier-buyer interdependency.

***Module Level*:** Modules are created by a combination of different parts from the Component Level, be electrical, mechanical, or chemical. For example, a windshield wipers controller is produced with a set of electrical components (e.g., resistors, capacitors, transistors, semiconductor chips, printed circuit board, etc.), mechanical components (e.g., housing and connectors), and chemical components (e.g., silicon, epoxy and solder). Similarly, motors, blades, wiper arms, and wiper switch modules are also formed from elements of the Component Level. Then, these modules are assembled together to produce a Sub-System Level component, the windshield wipers system. The design and manufacturing of modules by an outsourced supplier must keep up with the technological innovation demands and specification compliance of a particular system. Often the existing modules sold in the market are designed to satisfy some specific sub-system or system specifications. Most modules are rarely universal in nature because they can not satisfy the technical requirements and demands of all systems, even if they serve the same applications.

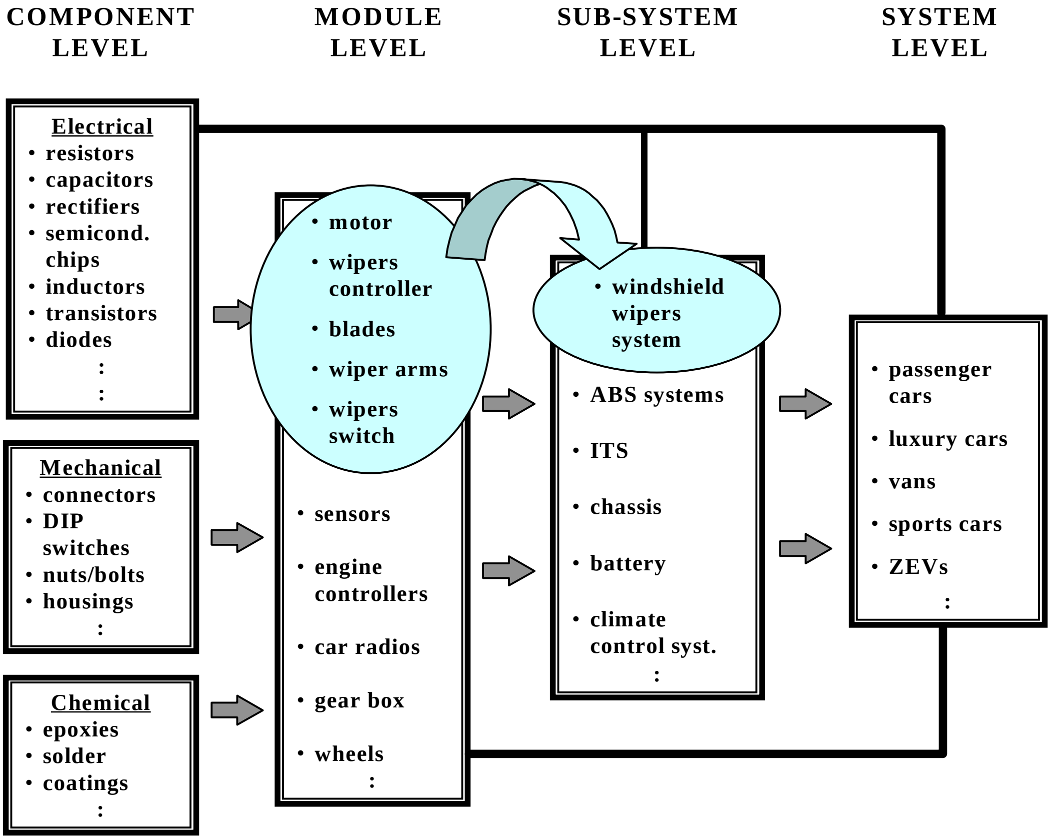

Figure 1. Different levels of modularization in automobiles.

***Sub-System Level*:** Components in the Sub-System Level are often highly customized for a particular system. In the case of automotive industry, there are numerous suppliers designing and manufacturing unique modules dedicated to a particular line of cars. For example, the Lincoln RESCU system (Remote Emergency Satellite Cellular Unit) is manufactured by Motorola and, was developed in partnership with Ford Motor Co. and Westinghouse Electric Corp. (Motorola 1995 Summary Annual Report). RESCU is designed to fit into Lincoln vehicles only. Similarly, the gearboxes installed in buses or ABS system for passenger cars are incompatible with the ones installed in racing cars or electric vehicles. This implies that interface and protocol compatibility between modules and sub-systems are absolutely essential for a system to function. Sometimes Sub-System Level modularization is bypassed or non-existent where modules are brought together and assembled at the System Level where the degree of supplier-buyer interdependency and interface constraints are much higher.

***System Level*:** Systems in this context are similar to Tushman and Rosenkopf's (1992) description of "closed assembled systems" where the system is enclosed by subsystems with clear boundary, and the individual subsystem must be linked together via interface and linkage technologies. Examples of systems include automobiles, airplanes, watches, and televisions. They are outcomes of the combination of elements from Sub-System, Module, or Component Levels. As new components are created at each level, modularization becomes more restricted at the System Level. Opportunities for modularization are significantly reduced as the interface compatibility effects increase. Degree of component customization, degree of value inputs, and degree of supplier-buyer interdependency also tend to be the highest. Interface constraints are highest at this level because the designers of the modular system must have a fairly good understanding of the overall product and its processes in order to develop and specify the design rules well in advance.

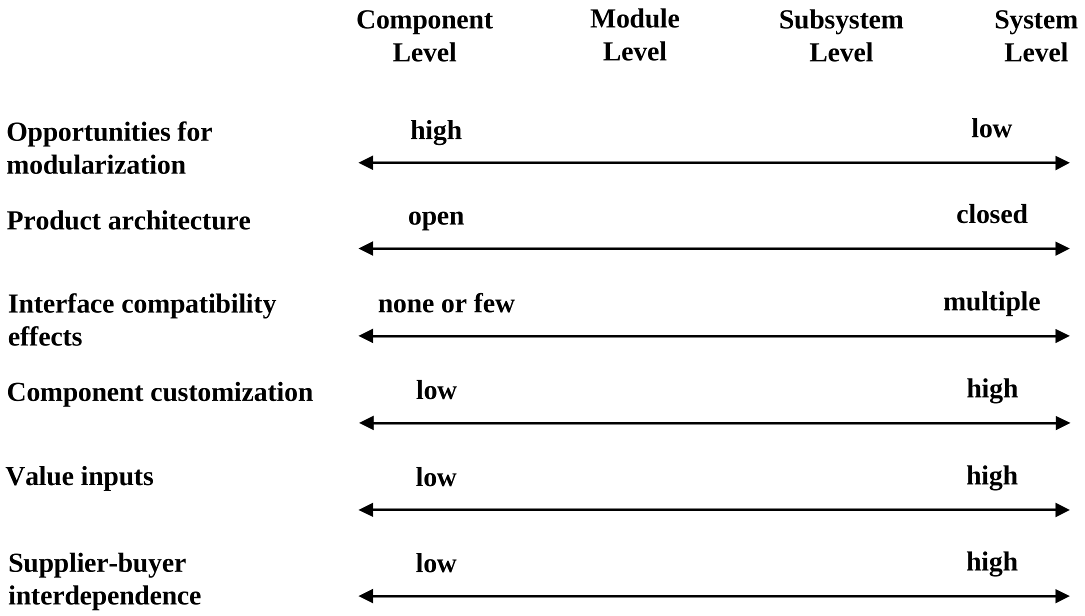

Figure 2. Characteristics of different levels of modularization.

Modularization, be at Component Level or at System Level, require companies to understand products at a deep level and be able to predict how modules will evolve over time. It also shortens the time business leaders have to respond to competitors' moves because it boosts the rate of innovation (Baldwin and Clark, 1997). If modularization in NPD is to have any strategic value to the firm, it is necessary to understand the different requirements and characteristics posed by modularization and its respective level of analysis. The opportunities for modularization, product architecture, interface compatibility effects, component customization, value inputs, and supplier-buyer interdependence vary from Component Level to System Level, as shown in Figure 2. Degree of component customization, value inputs, and degree of supplier-buyer interdependence tend to be low at the Component Level, characterized by open architecture products with none or few interface compatibility effects. As modules and subsystems are created, the degree of component customization, value inputs, and supplier-buyer interdependence become higher at the System Level.

3. In-house Development vs. Outsourcing

When a new project has been given the green light to start the development, its activities and processes can be analyzed in three stages: planning, design and manufacturing. The planning phase activities are often related to the definition of functional specification of the new product such as general product definition, lead time requirements, and definition of interface specifications. The design and manufacturing stages are often referred to as the detailed engineering phase where bill of materials and blue prints are generated, prototypes are built and tested, manufacturing processes and equipment are selected and qualified, and so on, as shown in Figure 3.

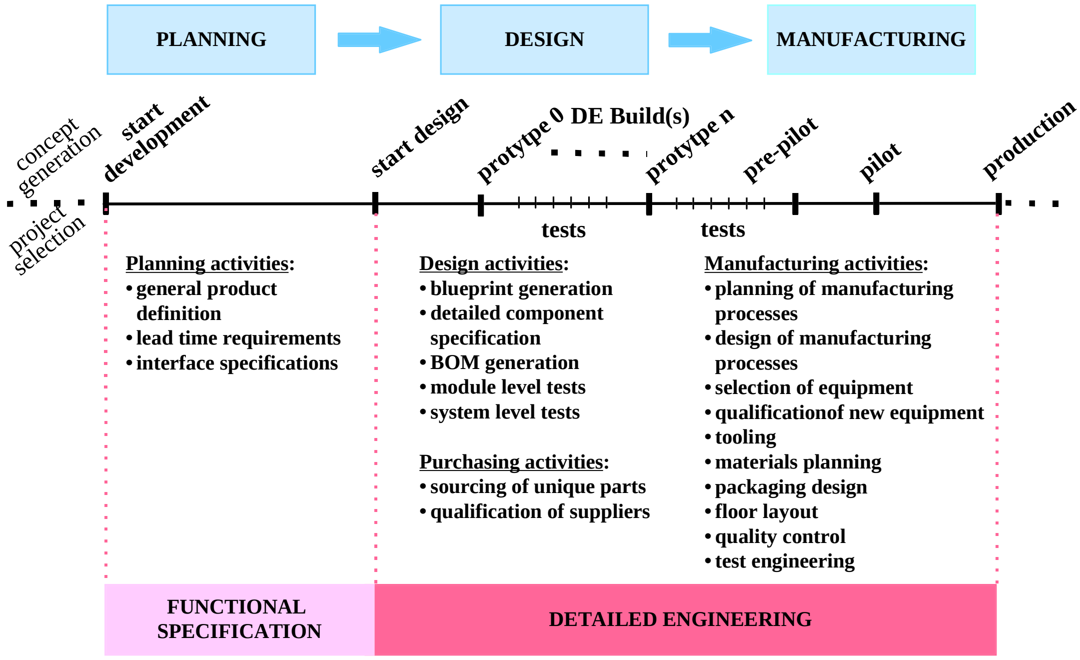

Figure 3. New Product Development Activities

The maker or assembler of a system basically faces two alternatives to manage the development of its components. The development activities of a component can either be carried out in-house or be outsourced. Depending on the proprietary sensitivity of the component and the degree of supplier involvement in design and manufacturing, the outsourced component can be further classified into three categories: supplier proprietary part, detail controlled part, and black-box part. In addition, the supplier involvement in engineering can be characterized by the degree of functional specification and detailed engineering responsibilities carried out by the supplier (as shown in Figure 4).

Supplier proprietary parts - Both functional specification and detailed engineering are performed by the supplier. There is almost no supplier involvement in the assembler’s engineering decisions. The assembler (or buyer) can treat these parts either as standard components (e.g., resistors, diodes, integrated circuits, etc.) or as highly customized parts (e.g., Intel microprocessors, digital signal processing chips, etc.).

Detail controlled parts - Both functional specification and detailed engineering are the responsibilities of the buyer. These parts often are assembler’s patented or proprietary parts. Build-to-print components fall into this category, in which case only the manufacturing activities are outsourced. The detail controlled parts (such as microprocessors with proprietary software codes) and bill of materials (BOM) are often supplied and pre-defined by the assembler, making the supplier’s involvement in the engineering activities limited. Some examples of detail controlled parts include mother-boards for computers, engine controllers, and some OEM goods.

		Detailed Engineering	
		Supplier	**Buyer/Assembler**
Functional Specification	**Supplier**	**SUPPLIER PROPRIETARY PARTS**	**“QUESTION MARK PARTS”**
	Buyer/ Assembler	**BLACK-BOX PARTS**	**DETAIL CONTROLLED PARTS**

Figure 4. A Framework for Defining Supplier Involvement in Engineering.

Black-box parts - While the functional specification is set by the buyer, the detailed engineering responsibility lays completely in the hands of the supplier. Depending on the complexities of the part, the supplier’s involvement in the assembler’s engineering activities become more significant. The success (or failure) and added value provided by the of outsourcing of a black-box part is highly depended upon the willingness of the parties to share and collaborate in solving technical problems related to interface compatibility effects.

“Question mark parts” - Due to the sequential nature of the NPD process (Figure 3), it is almost not feasible to have the functional specification of a part be defined by the supplier while the buyer is responsible for the detail engineering. This case may only be existent in Japanese practices where the operations and planning are highly integrated. For example, Toyota's and Nissan's suppliers invest in developing ideas and plans for the next model well in advance. Both the supplier and buyer engineers have long-term experience working together, making it easier to rapidly develop designs for the next model (Dyer and Ouchi, 1993).

3.1. The Role of Modular Innovation in Black-Box Design

Henderson and Clark (1990) defined modular innovation as 'an innovation that changes only the relationships between core design concepts of a technology. It is an innovation that changes a core design concept without changing the product's architecture.' Similarly, Christensen and Rosenbloom (1995) described it as 'the introduction of new component technology inserted within an essentially unchanged product architecture.'

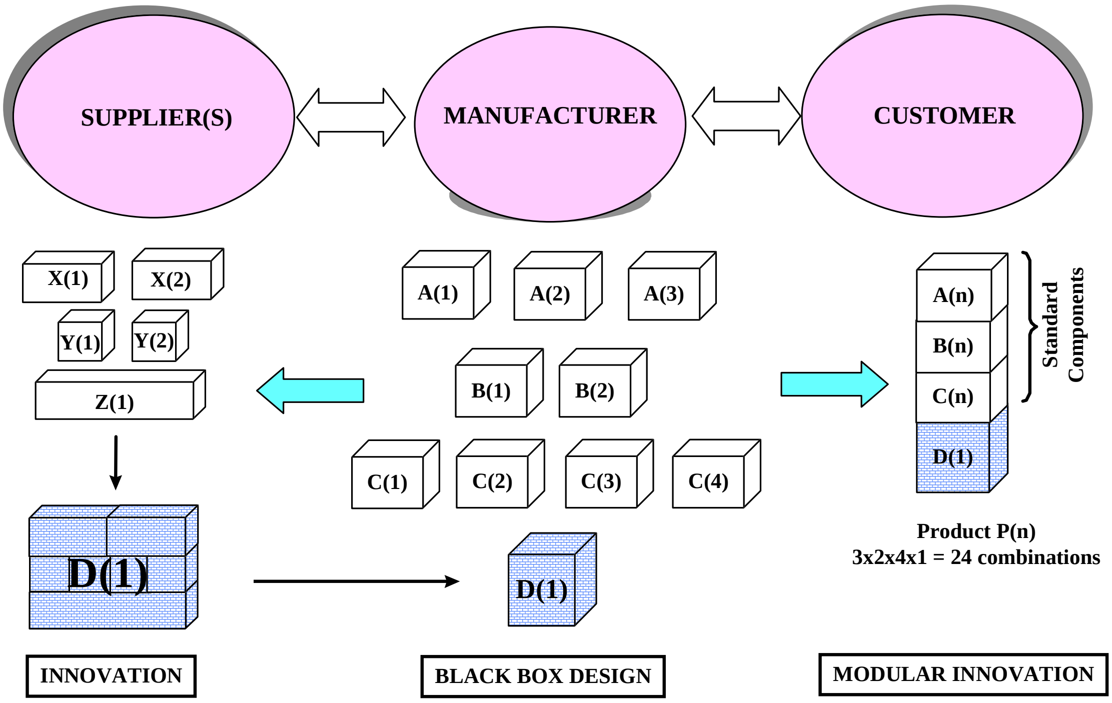

Figure 5. Modular innovation and its role in black-box design.

The modular innovation and its role in black-box design can be represented by Figure 5. Consider a manufacturer faced with the task of delivering a black-box part. Often the budget allocated to the project is limited with a very challenging detail engineering time table. This means that design lead time is compressed, therefore not much room for trial-and-error experiments to take place. Under such scenario, the best solution is to produce the black-box part with as many standard components [e.g., A(n), B(n), and C(n)] as possible, thus lowering the product cost, sourcing risks, and at the same time offering more mix-and-match opportunities for the customer [e.g., product P(n) allow for 24 combinations]. The caution here is that a product designed completely with standard components can be very easily copied and reverse-engineered by competitors. Thus, one solution is to design the black-box with some specific state-of-the-art, proprietary technology [e.g., D(1)] so that its accessibility is limited, at least in the short-run. In black-box design, the functional specification such as general part definition, lead time requirements, and interface specifications are defined by the customer, therefore it is assumed that the product architecture remains unchanged. Product P(n) is then, a modular innovation with innovation D(1), a core design concept, built in it.

Similarly, the manufacturer can also outsource some of its components as black-box parts to its suppliers, as in the case of D(1). Such innovation or state-of-the-art technology is likely to be designed and manufactured by a supplier who possesses the specific knowledge and technical skills of the technology in question. Within the supplier's R&D organization, different sets of components and technologies [e.g., X(n), Y(n), and Z(n)] are used in order to produce the innovation D(1). Commercialization risks in black-box design are usually minimized for the suppliers in the sense that the innovation is developed based on the manufacturer's (or customer's) functional specifications.

4. The Characteristic Curve of Modularization

The characteristic curve of modularization is a function of the opportunity for modularization (y-axis) and interface constraints (x-axis), as shown in Figure 6. For each level of modularization there is a corresponding interface constraints and an opportunity for modularization. Specifically, the interface constraints are a function of the component customization, interface compatibility effects, value inputs, and supplier-buyer interdependence. The opportunity for modularization diminishes in a non-linear fashion from Component Level to System Level as interface constraints increases.

At the Component Level, opportunities for modularization are highest because there are infinite ways in which standard components can be combined to create new modular product designs at the Module Level. Interface constraints tend to be minimal because component customization, value inputs, and supplier-buyer interdependence are low at this level. Notice how a small change in the opportunities for modularization allows for a fairy large change in the interface constraints at this level. This suggests that changes in component customization, supplier-buyer interdependence, and value inputs have little effect on the opportunity for modularization.

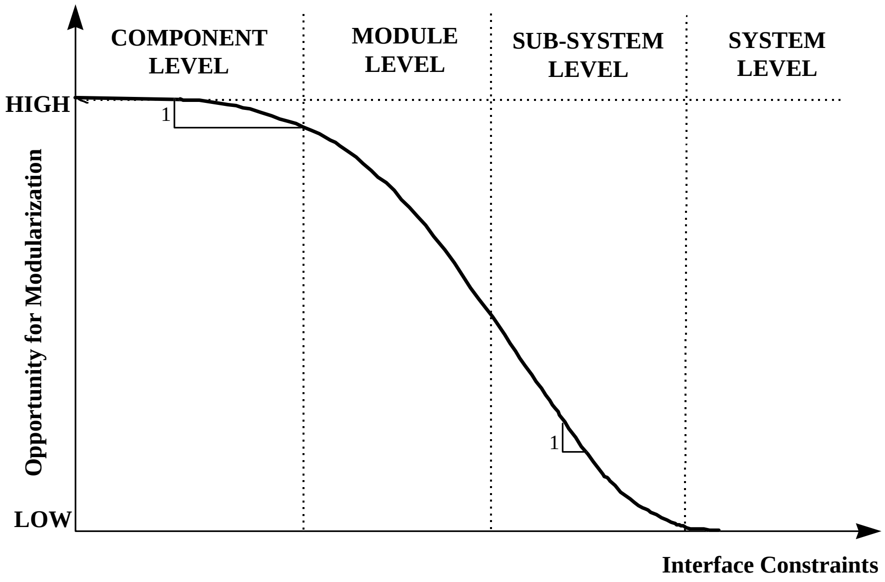

Figure 6. The Characteristic Curve of Modularization.

At the Module and Sub-System Levels, modularization becomes more restricted. The functional performance of the module must comply with the sub-system specifications, and sub-system with system specifications. Thus, the number of available modules in the market place compatible with the sub-system or system is limited. Any change of interface specifications in one module can impact the functionality and performance of the system. Therefore, interface constraints at Sub-System Level is much more sensitive than at the Component Level, reducing the opportunities for modularization even more.

As the characteristic curve portrays, a small change in the opportunities for modularization allows for a fairly small change in the interface constraints at the Sub-System Level, but a large change at the Component Level. This implies that the scope of modularization sensitivity, or the slope of the characteristic curve, at the Component Level is much smaller than at the Sub-System Level. In other words, opportunities for modularization are less sensitive to changes in interface constraints at the Component Level than at other levels. The slope of the curve, or scope of modularization sensitivity, indicates the ratio between the rate of change of the opportunities for modularization and the rate of change of interface constraints.

$$\begin{array}{c}\textit{Scope of Modularization} \\ \textit{Sensitivity}\end{array} = \frac{\textit{Rate of Change of Opportunity for Modularization}}{\textit{Rate of Change of Interface Constraints}}$$

At the System Level, opportunities for modularization is practically zero. Most firms opt to offer products and/or systems that somewhat can be differentiated from competitors’ products. Incompatibility among similar systems offered in the market is important and strategic in nature for firms because it has a great impact on after-sales service, warranty policies, spare parts management, future system enhancements, and how customers can become locked into the system and its accessories. The development of universal systems is avoided because they tend to reduce a firm’s competitive position in the market place, unless the firm already has a significant portion of the market share. Moreover, the amount of proprietary technology employed in universal systems is usually minimal, which is uncharacteristic of innovations[5].

4.1. The Modularization Envelope

As the curve moves down from Component Level to System Level, the slope becomes steeper indicating the increasing scope of modularization sensitivity. As mentioned, the degree of supplier-buyer interdependency can influence the outcome of modularization. The more interdependent they are of each other, the more likely is for the success of the modular innovation to take place. Assume that there is a characteristic curve for each closed system. Manufacturers offering competitive systems often encounter completely different sets of interface constraints, and that the opportunities for modularization can be influenced by the nature of partnerships shared between the parties. Then a set of characteristics curves (f_0, f_1, … , f_n) forms the 'Modularization Envelope', as illustrated in Figure 7. The modularization envelope assumes that there are two contrasting types of relationships or partnerships shared: 'durable arm's length relationships' and 'strategic partnerships.'

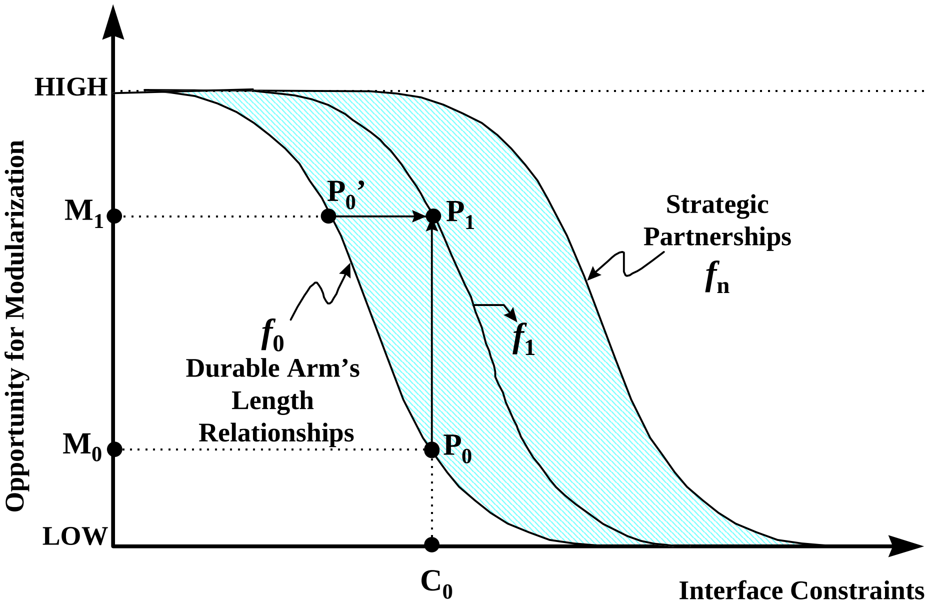

Figure 7. The Modularization Envelope.

Whether the parties are satisfied with the outcome of the partnerships depends on the products (or innovations) developed and supplier management practices. In other words, the nature of partnerships can vary from one extreme, a *durable arm's-length relationship,* to the other extreme, a *strategic partnership*. The contrasting characteristics of these two models of partnerships in terms of product/input

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[5] Although new markets are created through the convergence of different systems (e.g., personal computers, electronic commerce, etc.), it is beyond the scope of this study.

characteristics and supplier management practices are described in Table 2 (adapted from Dyer et al., 1998).

The success or failure of modularization in new product development is expected to vary depending on the nature of the supplier-buyer partnerships. For firms pursuing the durable-arm's-length type of relationships, the products are often open architecture, commodity products with few interaction effects with other inputs, consequently the interface constraints are at their minimum. In contrast, firms pursuing strategic partnerships with its suppliers or customers, products designed are often closed architecture, customized products with multiple interaction effects with other inputs, consequently interface constraints are at their maximum. Given these two streams of partnerships, the supplier-buyer interdependency is also expected to change from arm's length relationships to strategic partnerships.

Table 2. Contrasting Durable Arm's-Length Relationships with Strategic Partnerships (Dyer et al., 1998).

	Durable Arm's-Length Relationships	**Strategic Partnerships**
Product/Input Characteristics	▪ Commodity/standard products ▪ Open architecture products ▪ Stand alone (no or few interaction effects with other inputs) ▪ Low degree of supplier-buyer interdependence (sequential interdependence) ▪ Low value inputs	▪ Customized, non-standard products ▪ Closed architecture products ▪ Multiple interaction effects with other inputs ▪ High degree of supplier-buyer interdependence (reciprocal interdependence) ▪ High value inputs
Supplier Management Practices	▪ Single functional interface (i.e., sales to purchasing) ▪ Price benchmarking ▪ Minimal assistance (minimal investment in interfirm knowledge-sharing routines) ▪ Supplier performance can be easily contracted for ex ante ▪ Contractual safeguards are sufficient to enforce agreements	▪ Multiple functional interfaces (e.g., engineering-to-engineering, manufacturing-to-manufacturing) ▪ Capabilities benchmarking ▪ Substantial assistance (substantial investments in interfirm knowledge-sharing routines) ▪ Supplier performance on non-contractibles (e.g., innovation, quality, responsiveness) is important ▪ Self-enforcing agreements are necessary for optimal performance (e.g., trust, stock ownership, etc.)

Assume, for example, that a high-tech product P_0, a point in characteristic curve f_0, has a set of interface constraints C_0 with M_0 opportunity for modularization. The producer of P_0 practices the durable arm's-length relationship with its suppliers. A competitor, on the other hand, has a similar product P_1 facing the same interface constraints as product P_0, but with a much higher opportunity for modularization M_1 (characteristic curve f_1). The supplier of P_1, however, is more willing to innovate and to aid the customers in finding better solutions in product development and manufacturing processes. Clearly, product P_0 is at a disadvantage to product P_1. In order for product P_0 to be at the same level of modularization as P_1, the P_0'P_1 shift must take place. This means that product P_0 has to modify its current product/input characteristics and supplier management practices (as described in Table 2) from a durable arm's length relationship towards a strategic partnership in order to the competitive with product P_1.

5. A Case Analysis

The front windshield wipers system for Chrysler Jeeps (Grand Cherokee, Cherokee, and Wrangler lines), illustrated in Figure 8, is comprised of a motor, wiper arms, blades, wash pump, wipers switch, and the wipers controller module (referred to as WIPER). Triggered by the wiper switch, it controls the following functions: High Speed (fast continuous wipes), Low Speed (regular continuous wipes), Intermittent (wipe intervals between 0.2 and 2.0 seconds), Mist (single wipes), and Wash (three consecutive wipes when water pump is activated). The wipers switch is located inside the vehicle near the steering wheel, and acts as a switch for windshield wipers. When a desired functionality is set at the wipers switch, WIPER sends the proper command to the motor controlling the windshield wipers.

In 1993, when Jeep Grand Cherokee was first introduced in the market as a high-end utility vehicle, a whole line of innovations and concepts were incorporated in it which were drastically different or not present in other Jeep models. Intermittent front-windshield wipers switch, WIPER controller, remote keyless entry, and vacuum fluorescent display monitor are some examples of electrical modules that were incorporated into the vehicle for the first time. These new innovations would provide significant improvement in performance, functionality and aesthetic looks compared to the existing Jeep models. In this case, the tasks and responsibility for the design and manufacturing of WIPER was outsourced to a world class manufacturer by Chrysler. The WIPER was considered a 'black-box' component because while the functional specification was Chrysler's responsibility, the detailed engineering including design and manufacturing was the responsibility of the supplier. Such activity resulted in two different technological solutions to the design of the module: 'solid-state' approach and 'silent-relay' approach. All the information presented in this study are the results of the author's personal hands-on involvement in the product design, manufacturing, and sourcing tasks of the WIPER.

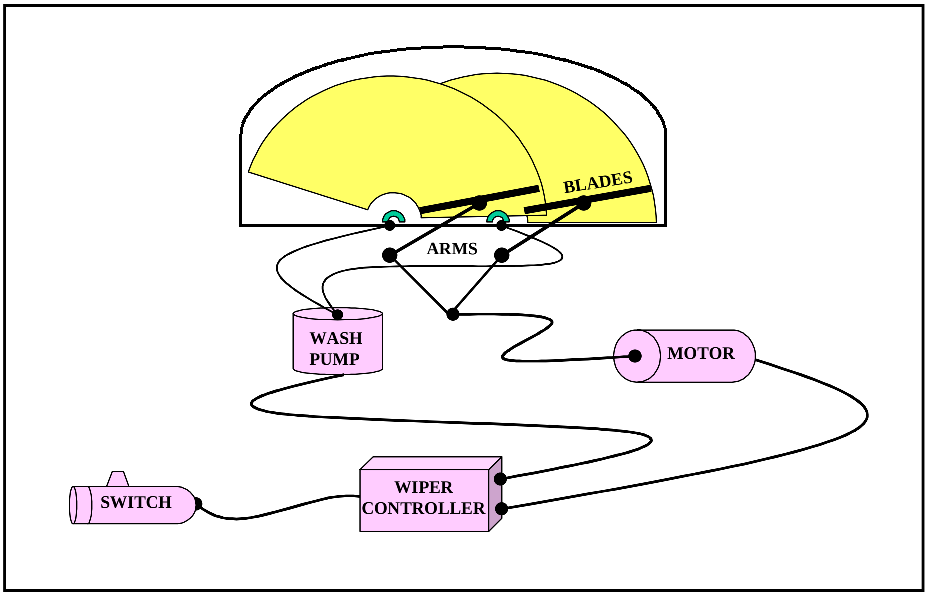

Figure 8. Windshield Wipers System.

The old WIPER controller modules used standard-relay-based technology which made ‘clicking’ noises when switching from one state to another (e.g., ON and OFF), a very annoying feature to some customers. So one of the solutions to defeat such annoyance was to apply ‘solid-state’ technology of which only transistors and other electrical components are used to perform the task of ‘switching,’ thus virtually ‘soundless.’

The solid-state WIPER was eventually abandoned and considered a failure. But it was a caveat for the subsequent success of the silent-relay WIPER. One of the lessons learned from the silent-relay WIPER was that the prototypes should have been tested at the wiper system level, not at the module level. A closer technical collaboration between the manufacturer and Chrysler was essential in order to ensure proper functionality of the entire wiper system. The relative performance characteristics of the solid-state WIPER and the silent-relay WIPER with respect to the old module are compared, as shown in Figure 9.

Opportunities for Modularization: The solid-state WIPER offered less opportunity for modularization as compared to both the old module and the silent-relay WIPER. The old module accommodated both the Cherokee Jeeps and Wrangler Jeeps. While the solid-state WIPER could only be used in Grand Cherokee Jeeps, the silent-relay WIPER was compatible with all three lines of Jeeps.

Product Architecture: Because the WIPER is considered a black-box part (all functional specifications of the module are determined by Chrysler while detailed engineering responsibility rests with the supplier) with a common set of interface constraints, the product architecture is the same for all three modules.

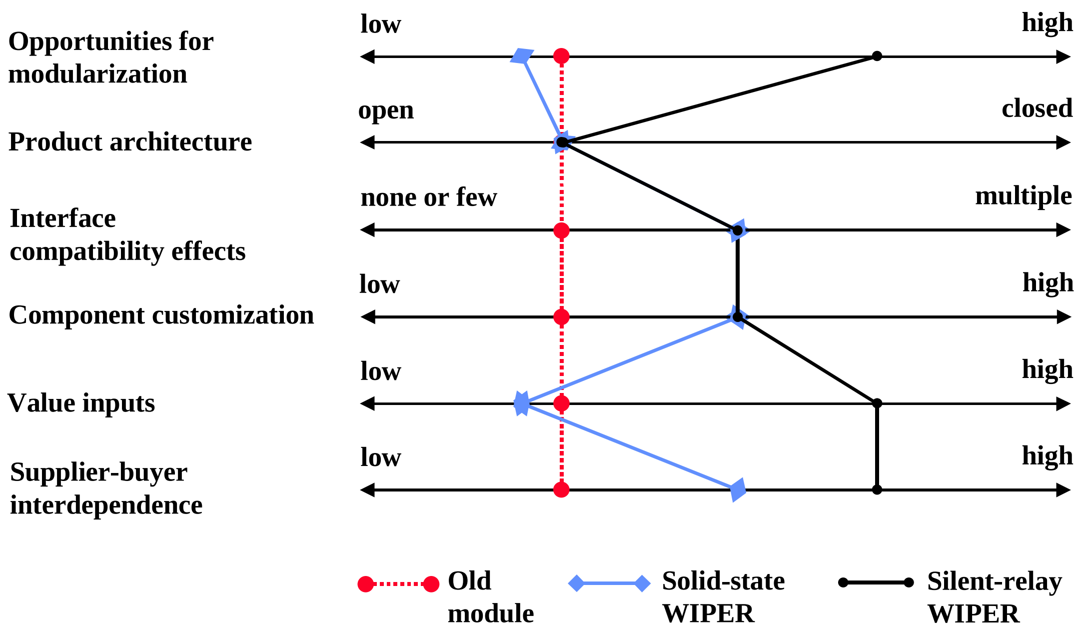

Figure 9. The relative performance of WIPER modules.

***Interface Compatibility Effects*:** Initially, the electrical specifications for the solid-state WIPER was set based on the old module. Being a new line of Jeeps, the interfaces among different modules in the wiper system were not quite the same as the current Jeeps. Interface compatibility effects for the solid-state and silent-relay WIPERs were more challenging than the old module due to the replacement of components with different interface characteristics and/or provided by new suppliers: the WIPER, the switch, and the windshield. More specifically, the different electrical properties of the new switch in addition to the slight change in the windshield angle (which required a new profile for the wiper bladed) altered the mechanical and electrical properties of the Grand Cherokee's wiper system.

The effects of interface compatibility became evident during the first prototype tests of the solid-state WIPER. The prototypes, when tested in labs as black-boxes, did not present any problems. Tests at the windshield system level, however, proved troublesome. Electrically speaking, the slight change in the windshield angle had increased the loading resistance, thus demanding more power from the WIPER. The module, under normal driving conditions (mild rain, 25^{o}C, slight wind, etc.), did not present any abnormalities. At some extreme operating conditions such as very high or low temperatures, however, where windshield wipers had to accommodate heavy loads, the solid-state-WIPER did not operate as desired. In some instance the WIPER would overheat and resume functionality. As the wipers system is considered a safety item, it must be fully functional in all critical operating conditions. The slight change in windshield angle seemed insignificant at first, but the impact of such change was so severe that it warranted the concept of solid-state-WIPER totally useless. Although the solid-state module was eventually considered a failure and abandoned, it was a caveat for the subsequent success of the silent-relay WIPER. It showed that a fairly good understanding of the entire windshield wipers system was necessary in order to ensure proper functionality of the WIPER.

***Component Customization*:** Equivalently, the degree of component customization is the same for both the solid-state and the silent-relay WIPERs, as they are both non-standard modules designed and manufactured to improve the performance over the old module (e.g., elimination of the ‘clicking’ noise).

***Value Inputs*:** The most significant difference among the three modules is in terms of the added value they provided as an input to the Jeeps. Interestingly, the solid-state WIPER provided even less value input than the old module because it was considered a failure. The silent-relay WIPER, on the contrary, provided significantly more value than the other two modules. Due to the failure of the solid-state module, the WIPER had to be redesigned. By then, a great deal of manufacturing processes had been designed and laid out accommodating the solid-state WIPER. So, to design a new module from scratch was not feasible. That was when the design team came up with the solution of keeping the majority of the solid-state WIPER intact, and to modify a portion of the electrical design by replacing it with a ‘silent relay.’ One of the advantages of relay-based technology for this application is that it would increase the robustness of the WIPER. Such ‘silent relay’ would have the properties of standard off-the-shelf relays, but would have significantly lower switching-noise level. The only problem was that there were no such devices on the market. Thanks to a very efficient sourcing team and close coordination with the design team, some 15 prototypes of silent relays from suppliers all over the world were tested and evaluated within less than one year. At the end, a Japanese firm was chosen as the sole supplier because it was able to offer the best performing silent relay with the most competitive price. The silent relay proved to be the key factor for allowing modular design and modular innovation to take place. With it, not only Jeep Grand Cherokee’s WIPER is ‘noise-free,’ other Jeep lines (Cherokee and Wrangler lines) could also use the same module. This meant that a common WIPER could be mounted on all Jeeps without any degradation in functionality and performance, accounting for differing electrical and mechanical properties of different wiper switches and windshield angles. The financial potential for the manufacturer of such realization was exhilarating. The silent-relay WIPER not only improved the overall performance over the old module, it also increased the production volume significantly (almost three-fold), not mentioning the sharing of common parts and assembly processes, and savings in tooling costs for the manufacturer. Positive rewards gained by Chrysler from such modular innovation were projected in the form of superior performance superiority, better understanding of system constraints for the next-generation of Jeeps, and cost savings in logistics and production. For the Japanese supplier, the realization of the ‘silent-relay’ allowed it to offer a complete new family of relays so new business opportunities are created for other non-automotive markets. The positive impacts and added value of the modular innovation of silent-relay module are listed in Table 3.

Table 3. Impacts of Modular Innovation.

IMPACTS OF MODULAR INNOVATION (Jeep's Silent-Relay WIPER Controller Module)	
Supplier	▪ The 'silent relay' created a new family of products ▪ New business opportunities in non-automotive markets
Manufacturer	▪ More intimate and trustworthy relationship and partnership with the customer as well as the supplier ▪ Future businesses with the customer and the supplier ▪ Savings in production cost: economies of scale in components, universal tooling, one common assembly line accommodating all modules ▪ Organization learning ▪ Profitability
Customer	▪ Performance superiority: significant reduction in switching noise level ▪ Better understanding of windshield wipers system constraints ▪ Cost savings

Supplier-Buyer Interdependence**:** The old module was considered as a standard component, therefore technical collaboration between Chrysler and the former supplier resembled that of a 'durable-arm's length' relationship. The introduction of the Grand Cherokee Jeep in addition to the outsourcing of the design and manufacturing activities to a new party called for a change in the nature of the supplier-buyer relationships. The more willing Chrysler and the manufacturer were to collaborate in solving technical problems related to WIPER at the system level, the more trust was nurtured between the parties. The subsequent success of the silent-relay WIPER was attributed a great deal to the creative global sourcing strategy and the willingness of the manufacturer to include its customers and suppliers during the early phase of the design process.

The impact of the supplier-buyer partnerships in the characteristic curve is illustrated in Figure 10. The WIPER's modularization analysis is performed at the Module Level. Both the solid-state and the silent-relay WIPERs had to satisfy exactly the same performance and compatibility requirements dictated by the wiper system. Consequently, both modules had the same interface constraints, C_{WIPER}. The solid-state WIPER is represented by point A in the characteristic curve $f_{SOLID\text{-}STATE}$ with $M_{SOLID\text{-}STATE}$ opportunity for modularization corresponding to C_{WIPER} interface constraints. The electrical portion of the solid-state WIPER was designed entirely with standard, off-the-shelf parts. There was no need to include new suppliers into the process. Manufacturer's relationship shared with Chrysler was somewhat formal and contractual where the responsibility of the manufacturer was to build the WIPER per Chrysler's technical specifications. Not much technical collaboration was shared at this stage.

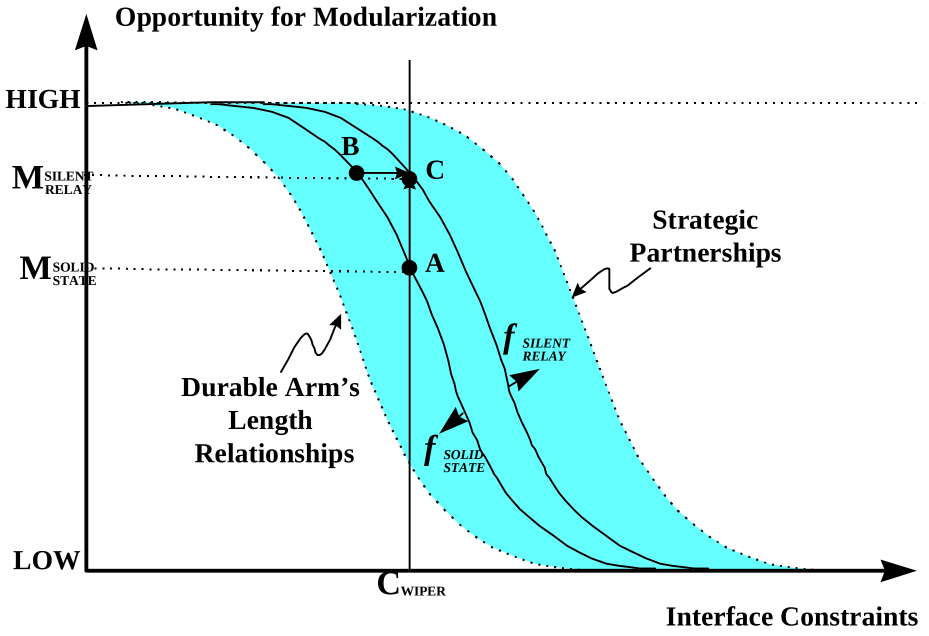

Figure 10. Characteristics Curve Analysis of Wiper.

Because of the lessons learned from the failure of the solid-state WIPER, both the manufacturer and the customer were more cautious and sensitive about the hidden constraints set by the wiper system. So, frequent visits to both the manufacturer and Chrysler sites in addition to daily phone calls became a norm. When the solid-state WIPER prototypes proved to be totally useless, new design approaches needed to be considered, and the manufacturer and Chrysler had to reconsider their current relationship to a more collaborative form. This meant that both parties had to work together as a team with the common goal of producing a performing module. This time around, proprietary information were shared so both parties had a clear understanding of each other's processes, capabilities, and constraints. Therefore, the silent-relay WIPER provided higher opportunity for modularization ($M_{SILENT\text{-}RELAY}$) in OEM's manufacturing processes as well as allowing Chrysler to use the same module in other Jeeps. This increase in opportunity for modularization shifts the WIPER's characteristic curve to a new one, $f_{SILENT\text{-}RELAY}$. The shift from point A to pint C is enabled by the modular innovation, the 'silent relay.'

The new supplier for the silent relay was also free to contact the manufacturer (in this case the design engineer in charge of the WIPER) at any time in case there are any technical specification clarifications. As a result of this trusting partnership and technical collaboration, Chrysler, the OEM, and the supplier experienced positive rewards. The improvement in the supplier-buyer partnership towards a strategic partnership is indicated by the shift of point B to point C in the characteristic curves, $f_{SOLID\text{-}STATE}$ and $f_{SILENT\text{-}RELAY}$ respectively.

6. Conclusion

This paper discussed the effects of modularization in black-box design and its impacts on supplier-buyer partnerships. Specifically, the relationship among different levels of modularization with respect to the opportunities for modularization and interface constraints was portrayed with a set of characteristic curves. For each level of modularization there is a corresponding interface constraints and an opportunity for modularization. The opportunity for modularization diminishes in a non-linear fashion from Component Level to System Level as interface constraints increases. The slope of the characteristic curves also revealed the scope of modularization sensitivity, that is, the ratio between the rate of change for opportunity for modularization and the rate of change of interface constraints. The paper also argued that the degree of supplier-buyer interdependency could influence the outcome of modularization. The more collaborative they are of each other, the more likely is for the success of the modular innovation to take place. In order to evaluate the how varying nature of partnerships, the contrasting characteristics of ‘durable arm’s-length relationships’ with that of ‘strategic partnerships’ were also analyzed vis-à-vis the characteristic curves.

The case of Chrysler Jeeps indicated that higher opportunity for modularization is possible when a more collaborative form of partnership is shared between the parties. The WIPER provided a valuable lesson about why critical interfaces should be defined and carefully evaluated in advance, whenever possible. It also showed that when modular innovation (silent-relay WIPER) is implemented properly, customers gain performance superiority of the products, better understanding of system constraints, and increased cost savings. The silent-relay WIPER was also the caveat for deepening the relationship and trust with Chrysler as well as with the supplier, not mentioning its significant impact on R&D and supply chain management next-generation products.

Although the paper only discussed the role of modularization in influencing supplier-buyer partnerships, it would be interesting to extend this study to include other factors of supply chain management such as mass customization and postponement. Furthermore, some intangible factors such as culture, knowledge management, and capability sharing of the organizations are difficult to measure, but they play an important role in orchestrating the supplier-buyer relationships. As companies increase their outsourcing activities, the role of strategic partnership in R&D and supply chain management will be indispensable.

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