Modularity assessment of product architecture: Implications for substitutability and interface management

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Modularity is a new product development strategy in which interfaces shared among components in a given product architecture become specified and standardized to allow for greater substitutability of components across product families. This paper introduces a mathematical model, termed modularization function, for analyzing the degree of modularity in a given product architecture by taking into account the following variables: number of components, number of interfaces, and substitutability factor of a given product architecture. It is assumed that the degree of modularity in a given product architecture is constraint by the composition of its components (number of standard and new-to-the-firm components), interfaces shared among the components, and degree of substitutability. The application of the modularization function is illustrated with two distinct sets of product architectures: Chrysler Jeeps windshield wipers controllers and transmission systems of Schindler elevators. The analysis of the Chrysler case shows that the silent-relay architecture achieved higher opportunities for modularization than the solid-state architecture due to the higher substitutability level and lower new-to-firm component composition. In the Schindler case, on the other hand, the comparative analysis of two different transmission sub-systems captures the sensitivity and dynamics of product architecture modularity created by three types of components (standard, neutral, and unique) and two types of interfaces (fundamental and optional). Some managerial implications for both case studies are also discussed based on the application of modularization function.

1. Introduction

In broadest terms, *modularity* (or *modularization*) is an approach for organizing complex products and processes efficiently (Baldwin and Clark, 1997), by decomposing complex tasks into simpler portions so they can be managed independently and yet operate together as a whole. Decomposition of a complex system into smaller, more manageable parts has been well discussed in management literature [e.g., scientific management principles with respect to standardized work designs and specialization of labor (Taylor, 1967)], sociology literature [e.g., nearly decomposable systems (Simon, 1995; 1996)] as well as in economics literature (e.g., Adam Smith's view on division of labor and task partitioning). A motivation behind decomposition of tasks is to gain flexibility and cost savings through economies of scale. Modularity in terms of maximizing economies of scale through standardization of components was already studied as early as 1900s[1].

From a system's perspective, modularity can be viewed as a continuum describing the degree to which a system's components can be separated and recombined, and it refers both to the tightness of coupling between components and the degree to which the "rules" of the system architecture enable (or prohibit) the mixing-and-matching of components (Schilling, 2000). Modularity permits components to be produced separately, or 'loosely coupled' (Orton and Weick, 1990; Sanchez and Mahoney, 1996), and used interchangeably in different configurations without compromising system integrity (Flamm, 1988; Garud and Kumaraswamy, 1993; Garud and Kotha,

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[1] For instance, inspired by Taylor's idea of using standard components, in 1913 the Ford T model reduced assembly time from 12 to 1.5 hours (Hsieh et al., 1997), hence creating the concept of mass production.

1994; Garud and Kumaraswamy, 1995). Standardizing component interface specifications (Sanchez and Mahoney, 1996) facilitates the degree of independence or ‘loose coupling’ between component designs.

There are many reasons why firms pursue modular modularization as a NPD. For one, modular product designs[2] enable firms to increase specialization (Langlois, 2000), encouraging them to pursue specialized learning curves and increasing their differentiation from competitors (Schilling, 2000) as well as benefiting from decreased throughput times with elimination of pre-assembly operations (Wilhem, 1997). Because modularity encourages concurrent and distributed component development processes, it enables the loose coupling of component designs and thereby creating loosely coupled knowledge domains (Sanchez, 1999). Modularity also boosts the rate of innovation, and as long as the design rules are followed, more experimentation and flexibility are given to designers to develop and test the modules (Baldwin and Clark, 1997) leading to rapid trial-and-error learning (Langlois and Robertson, 1992), specially important with innovations that change rapidly involving high degree of both technological and market uncertainty (Nelson and Winter, 1982). Other advantages of modularization include cost reduction (Muffatto, 1999; Garud and Kumaraswamy, 1995; Sanchez, 1996; Grave, 1994), economies of scale and scope (Sanchez 1999; Garud and Kumaraswamy, 1995; Friedland, 1994), increased flexibility (Schilling, 2000; Baldwin and Clark, 1997; Wilhem, 1997; Sanderson and Uzumeri, 1997; Christensen and Rosenbloom, 1995; Sanchez, 1995; Garud and

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[2] In 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).

Kumaraswamy, 1995; Henderson and Clark, 1990), and increased competition among suppliers (Langlois, 2000, 1992; Tassey, 2000; Sanderson and Uzumeri, 1997; Reed, 1996; Langlois and Robertson, 1992; Garud and Kumaraswamy, 1993; Morris and Ferguson, 1993).

Given all the alluring advantages of modularization, it seems to be an attractive strategy for many high-tech firms to gain competitive advantage. Modular products may protect a firm's market power and architectural control, specially when a firm possesses some unique assets, or accessibility to complementary assets (Teece, 1986), that enables it to resist the pressure created by customer demands for modular products (Schilling, 2000). But for how long can firms protect such assets from competitors and how are new assets created? A closer look reveals that in order to benefit from modularization a firm must have a broad and yet focused view about its technology and innovation management vis-à-vis its competitors, suppliers, and customers (Hsuan, 1999). The ability of firms to create superior product architectures are also depended on a firm's routines and capabilities (Nelson and Winter, 1982), and "inflexibility or 'inertia' induced by routines and capabilities can raise to prohibitive levels the cost of adopting a new technology or entering new fields" (Langlois and Robertson, 1995:105).

Modularity management of product architectures is strategic. In order for product architectures to gain some sort of sustainable competitive advantage[3] it should be

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[3] Sustained competitive advantage (Olavarrieta and Ellinger, 1996:565) is "a competitive advantage that is not easily replicated or eliminable, that can be maintained over a certain period of time and that is the origin of a firm's sustained superior performance."

inimitable (Dierickx and Cool, 1989; Baney 1991), at least in the short run, and create value for both the firm and its customers. Product configurations are rooted in product architecture designs. In assessing modularization at the product architecture level, issues regarding to decomposability and integration of disparate components vis-à-vis interface management of these components can not be taken for granted. Consequently, the degree of modularization inherent in product architectures is sensitive and highly dependent upon the number of components and the interface constraints shared among the components, modules, sub-systems, and systems. Many studies on modularization (c.f., Schilling 2000, Robertson and Ulrich 1998, Baldwin and Clark 1997, Henderson and Clark 1990, Garud and Kumaraswamy 1995, Sanchez and Mahoney 1996, Muffatto 1999) tend to be qualitative and exploratory in nature, and there is limited evidence from the literature providing a systematic way to analyze modularization at the detailed engineering level and how it impacts interface management of components in product architecture designs. It seems reasonable to say that firms should understand the fundamental relationships between components and interfaces at the root of product architecture in order to manage the modularization of products efficiently. If so, how can we systematically analyze the degree of modularization in product architectures? What are some tradeoffs between standard components (to gain from economies of scale) and unique components (to gain from product differentiation)? How does component substitutability impact the dynamics of modularity in product architectures?

A mathematical model is introduced in order to get a step closer at addressing these questions by looking at the fundamental relationships shared between components, respective interfaces, and substitutability of a given product architecture. Two distinct technological systems are analyzed for comparison: (1) Chrysler Jeeps

Windshield Wipers Controllers (relay-based and solid-state technologies) and (2) Schindler Elevators transmissions (traction and hydraulic). The paper is organized as follows. Firstly, a literature review of modularity and definition of variables in the mathematical model is presented. Secondly, the modularization function is introduced along with its assumptions for assessing the degree of modularity in given product architectures. Next, two distinct product architectures are used to illustrate how the model can be used. Finally, the paper concludes with some managerial as well as theoretical implications of the application of modularization function and avenues for future research.

2. Modularity in product architectures

Product architecture is the arrangement of the functional elements of a product into several physical building blocks, including the mapping from functional elements to physical components, and the specification of the interfaces among interacting physical components. Its purpose is to define the basic physical building blocks of the product in terms of both what they do and what their interfaces are with the rest of the device (Ulrich, 1995; Ulrich and Eppinger, 1995). In assessing modularization at the product architecture level, issues regarding decomposability as well as integration of components vis-à-vis how these components are linked become an important factor. At the heart of product modularity is the relationship shared among the components and respective interfaces in product architectures. The degree to which component interfaces are standardized and specified characterizes the level of interface constraint created by the way in which components are linked together, and defines the degree of modularity of a given product architecture. The degree of modularity is furthermore enhanced by the substitutability of components. In accordance with the level of analysis and the model used in this paper, modularity is defined as a new product development strategy in which interfaces shared among components in a given product architecture become specified and standardized to allow for greater substitutability of components across product families. Three important factors define the degree of modularity at the product architecture level: components, interfaces, and substitutability (Figure 1).

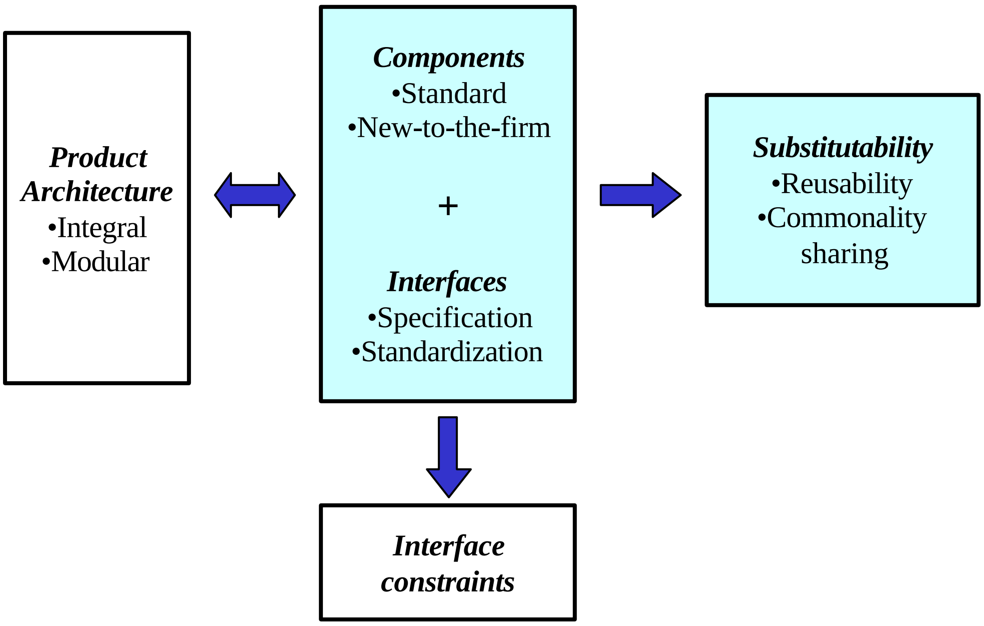

Figure 1. Fundamental elements of product architecture modularity.

2.1. Components

A component is defined as a physically distinct portion of the product that embodies a core design concept (Clark, 1985) and performs a well-defined function (Henderson and Clark, 1990). Firms typically classify components as standard or new-to-the-firm (NTF).

Standard components are often off-the-shelf parts, having well defined technical specifications with standardized interfaces, and are generally accepted as industry standards. These parts are often listed in catalogues with unit prices varying accordingly with the volume purchased. Possible interface compatibility issues with other components can be assessed quickly without incurring expensive testing costs. These components have well specified and standardized interfaces, hence product architectures comprised of standard components are highly modular.

New-to-the-firm (NTF) components, on the other hand, are components that are usually considered unique by a firm, as they are introduced into the product architecture for the first time, hence incurring higher technological risks than standard components. Interface compatibility issues with other components within the product architecture have to be re-evaluated, and sometimes this process can be costly and time consuming. Often the risks are well justified by the technical superiority of these components, significantly improving the overall performance of the product architecture. The use of NTF components is strategic in nature because the integration of NTF components into product architectures prevents imitation by the competitors (i.e., modular innovation), thus creating competitive advantages for the firm, at least in the short-run. But too many NTF components may delay product development lead time and increase the technological complexity of the product architecture. Contrary to standard components, interface specifications and hence interface compatibility issues of NTF components with other components of a given product architecture are not well understood. Consequently, introduction of NTF components into product architectures hinders modularity freedom.

2.2. Interfaces

Interfaces are linkages shared among components, modules, and subsystems of a given product architecture. Interface specifications define the protocol for the fundamental interactions across all components and interfaces comprising a technological system. Component interfaces can be specified according to the following (Sanchez, 1999): attachment, spatial, transfer, control and communication, environmental, ambient, and user interfaces.

The degree of interface specification of NTF components is depended on the technological innovation of such component with respect to the market. If the NTF component is new to the world, then its interface specification is bound to be ill specified. However, when the NTF component is unique only to the firm, then its interface specification is generally well defined within the industry, but not standardized within the firm. Only when the specification of NTF components becomes well specified and standardized within the firm that it becomes a standard component. Consequently, the compatibility among components is constrained by the degree of specification and standardization of interfaces.

2.2.1. Interface constraints

The extent to which components are linked is restricted by their characteristics (standard versus NTF) and degree of specification and standardization of interfaces. The compatibility of components within a given product architecture, hence, is constrained by the relationship shared between the components and respective interfaces. A component that is dependent on many other components (e.g., many interfaces) for functionality, for instance, imposes high interface constraints.

The level of interface constraint also indicates the relative ‘criticalness’ or ‘vulnerability’ of components in the architecture. For example, microprocessor (a component) in a motherboard (a PC sub-system) would be considered a critical part based on the number of interfaces shared with other components. In order for a microprocessor to function properly, it has to interface directly with a number of components, easily ranging from 56 to over 200 interfaces. Conversely, a capacitor would present lesser interface constraints than microprocessors. Typically, capacitors require two interfaces for functionality, a cathode and an anode.

2.3. Substitutability

One crucial element of modularity, especially in cases of modular innovations[4], is substitutability. Garud and Kumaraswamy (1995) used the term ‘substitution’ to suggest that technological progress may be achieved by substituting certain components of a technological system while reusing others, hence taking the advantages of economies of substitution. This has great implications for technological systems that are modularly upgradable. With economies of substitution, firms can reduce product development time, leverage past investment, and provide customers with continuity. The authors also suggest that firms reorganize their internal as wells as external relationships to reduce the costs of component reuse, while enhancing associated benefits. In order to capture the essence of economies of

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[4] Modular innovations are innovations that change only the relationships between core design concepts of a technology without changing the product’s architecture (Henderson and Clark, 1990). In other words, modular innovation is the introduction of new component technology inserted within essentially unchanged product architecture (Christensen and Rosenbloom, 1995). Here modular innovation is a case of NTF component.

substitution, they identified three system level attributes: integrity, modularity, and upgradability. According to Garud and Kumaraswamy (1993), economies of substitution exist when the cost of designing a high-performance system through the partial retention of existing components is lower than designing the system afresh. Substitutability factor has implications for the following:

- reusability and commonality sharing of next generation platform designs
- the potential for a high substitutability factor is obtained when components are designed with reusability and commonality sharing in mind

Economies of substitution are easier obtained with standard components than with NTF components. Components have to be compatible in order to be substitutable. Newly developed components, or unique components, may not fit or interact well with existing components, thereby compromising system integrity (Garud and Kumaraswamy, 1995). The substitutability of NTF components is extremely important product architecture designs, especially when the NTF can be used across other product families. Substitutability of NTF components also cuts across firm boundaries in spanning technological innovation, especially if the component is outsourced or co-developed with external parties.

3. Specification of Modularization Function

In order to capture the relationships and dynamics of modularity in product architectures, I apply mathematical modeling approach to find the relationship between degree of modularity in a given product architecture and the following variables: components, interfaces, and substitutability. One of the advantages of a mathematical model is that it allows us to synthesize a complex phenomenon into equations and functions, leading to a wide range of theoretical examinations and simulations of the phenomenon. Mathematical models are also powerful for analyzing dynamic behavior of the variables.

The amount of modularization in a given product architecture is a function of the composition of NTF components (or percentage of NTF components), substitutability factor, and interface constraint factor (both variables are function of number of components and interfaces). Refer to Appendix A and B for the formulation of the modularization function and interface constraint factor respectively. The modularization function, *M(u)*, decreases in a non-linear fashion from a perfect-modular architecture (i.e., no NTF components) to a perfect-integral architecture (i.e., no standard components):

$$M(u) = e^{-u^2/2Nsd} \qquad \text{Equation 1}$$

$M(u)$ - Modularization function

u - number of NTF components

N - total number of components

s - substitutability factor

d - interface constraint factor

In deriving the modularization function, the following assumptions are made:

1. NPD of a black box[5] is used, implying that the product's functional specifications, including interface specifications, do not change over a period of time. This

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[5] Buyers often consider components manufactured by an original equipment manufacturer (OEM) as black boxes, as they are treated as outsourced components.

assumption allows the evaluation of the architecture's configuration and components composition independently from other sub-systems.

2. A given product architecture is comprised of a combination of standard and NTF components.
3. It is argued that NTF components impose higher interface constraints. Therefore, the lower the NTF components composition in a product architecture the higher the degree of modularization.
4. Product architectures made entirely of standard components can be equally damaging as product architectures with high-NTF-component composition. It does not protect a product's technological content, and can be easily copied by the competitors. Thus, it is assumed that there should be some amount of NTF components in a product architecture.
5. All standard components are equally critical.
6. All NTF components are equally critical.
7. All interfaces are equally critical.

4. Comparative Case Analyses

The modularization function was first derived to analyze degree of modularization in a given product architecture of windshield wipers controller systems in Chrysler Jeeps (Mikkola, 2000a; 2000b; 2000c). Next, the model was also tested with two comparative transmission systems of Schindler Elevators (Mikkola, 2001; Mikkola and Gassmann, 2001). Although automobiles and elevators are different systems, the complexity of modularity imposed by components and respective interfaces can be translated into mathematical forms, hence making it possible for the systematic analysis of product architectures of dissimilar systems. The assessment of degree of modularization in a given product architecture, for both cases, involved the following steps:

1. Define product architecture and its boundaries.

2. Decompose the product architecture into sub-circuits, so that each one of the sub-circuits can be assessed individually.

3. Assess the substitutability factor of the black box by counting the number of product families enabled by the black box, divided by the number of interfaces required by the black box for functionality, in accordance with the level of analysis.

4. Count the total number of components comprising the product architecture. This can be accomplished by looking at the product's bill of materials.

5. Count the number of NTF components.

6. Compute the interface constraint factor, or the average number of interfaces per component, for each sub-circuit as formulated in Appendix A.

7. Plug these values into the modularization function (Equation 1) to find out the degree of modularization inherent in the product architecture.

4.1. Case A: Chrysler Jeeps Windshield Wipers Controllers

The Chrysler Grand Cherokee Jeep's windshield wipers controller (WIPER) [6] is a black-box module of which the functional specification was set by Chrysler and the detailed engineering including design and manufacturing was outsourced to a Fortune-100 OEM supplier. The block diagram of the windshield wipers' sub-system linkages is illustrated in Figure 2. Primary data was collected through examining schematic drawings, bill of materials, engineering log books, and other proprietary engineering data. The data is collected between 1991 and 1993, from the start of development date to full production date, in which the author served as the design team leader of the project.

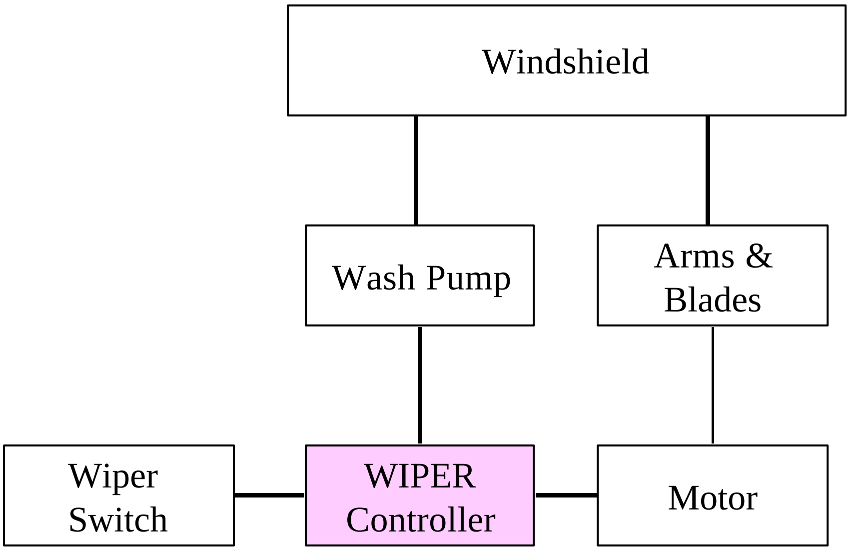

Figure 2. Block diagram of Jeeps windshield wipers system.

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[6] For a more thorough description of this case with respect to technological solutions, modular innovation and supplier-buyer interdependence, see Hsuan (1999a).

There were two different technological solutions to the design of the module: 'solid-state' approach and 'silent-relay' approach. The WIPER module used by Jeep models prior to the introduction of Grand Cherokee families applied standard relay-based technology which made annoying 'clicking' noises when switching from one state to another (e.g., ON and OFF), a feature that Chrysler wanted to get rid off with the new family of Jeeps. During the first attempt to defeat the 'clicking noise', a 'solid-state' approach was applied with the use of only transistors and electrical components. The product architecture of solid-state WIPER is consisted of the following sub-circuits: power supply, timer and enabling circuitry, oscillator, charge pump, short circuit protection, and driver circuitry (as shown in Figure 3).

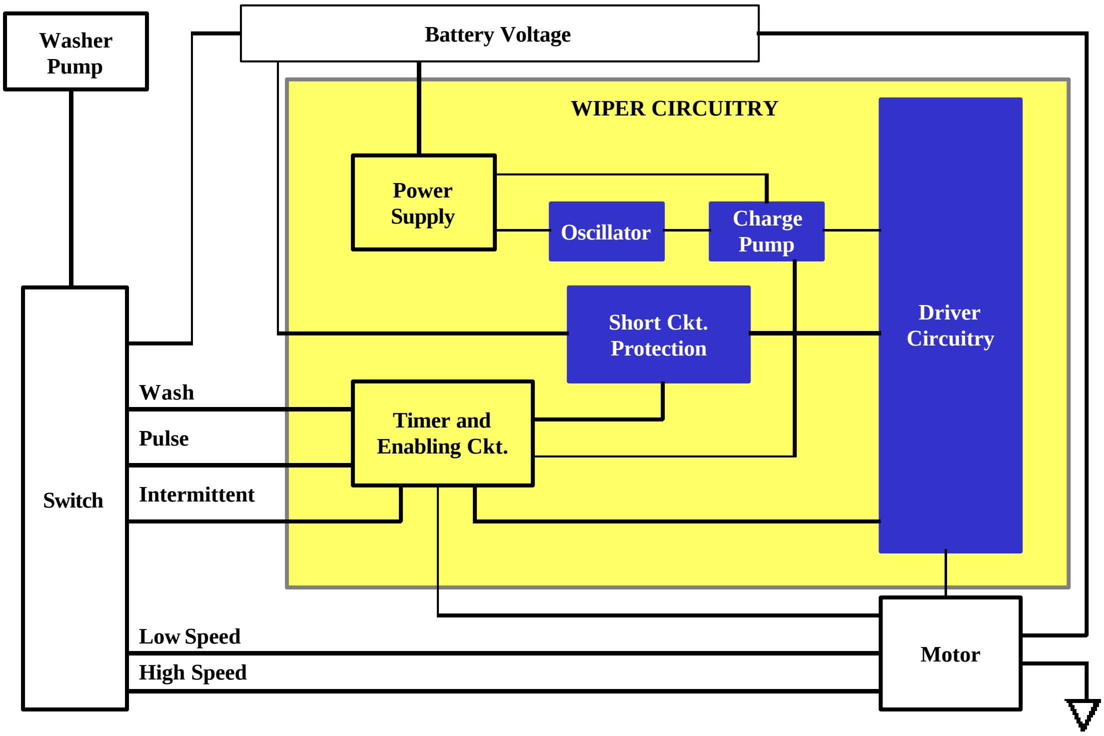

Figure 3. Product architecture of solid-state WIPER.

After almost a year of development, the 'solid-state' concept was a failure, contributed by the insufficient knowledge about the interface constraints shared between the WIPER with the rest of the windshield wiper's system. As Jeep Grand Cherokee was a new family of vehicles with many new technologies incorporated into it, not all the interface compatibility issues shared among the components, modules, and sub-systems were well understood. During the second attempt, a totally new innovation was developed to create the 'silent-relay' WIPER. In an effort to minimize design and manufacturing changes, 'silent-relay' and peripheral circuits replaced a portion of the solid-state WIPER. Although the changes were not drastic, nevertheless the relationships shared among the components and respective sub-circuits and interfaces were altered (as shown in Figure 4).

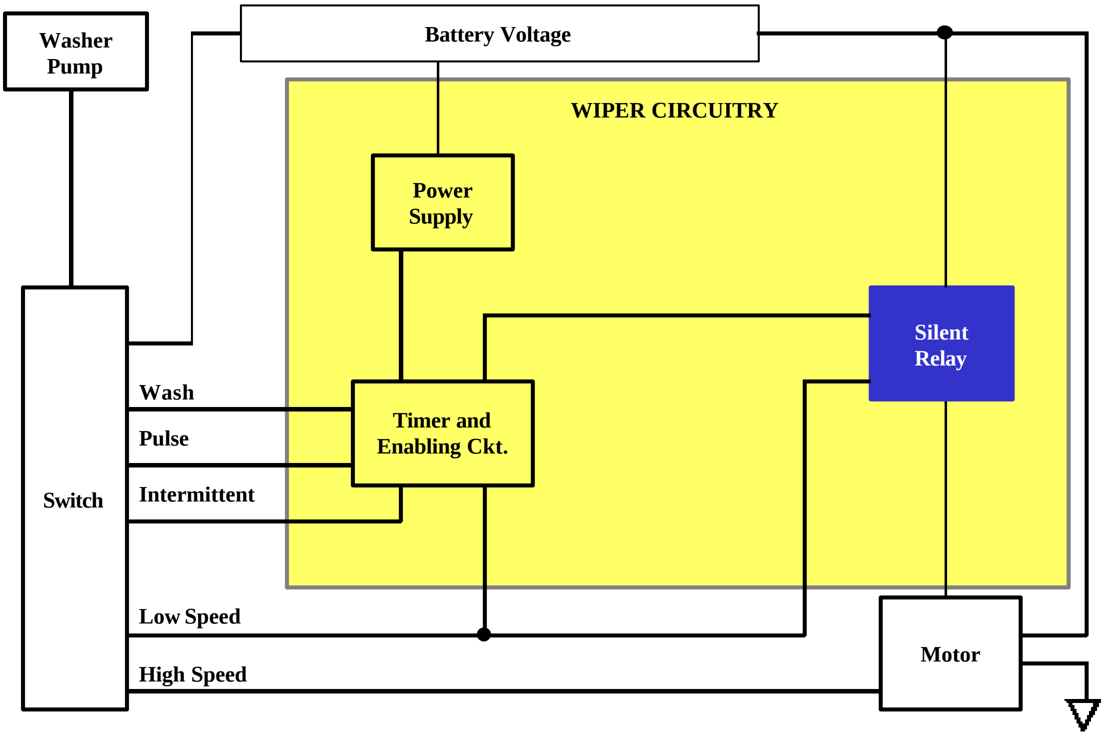

Figure 4. Product architecture of silent-relay WIPER.

In order to get a ‘feel’ for how components and respective linkages interact with one another to form the sub-circuits, we need to take a closer look at the constituents of individual sub-circuits, at the detailed product architecture level. In doing so, we will find that technical functionality of each sub-circuit is enabled by the discrete components and respective linkages. For example, the power supply sub-circuit[7] is comprised of three standard components (R1, C1 and VR1) with specific interfaces (as illustrated in Figure 5) in order to deliver proper oscillator and charge pump output signals from a common battery voltage.

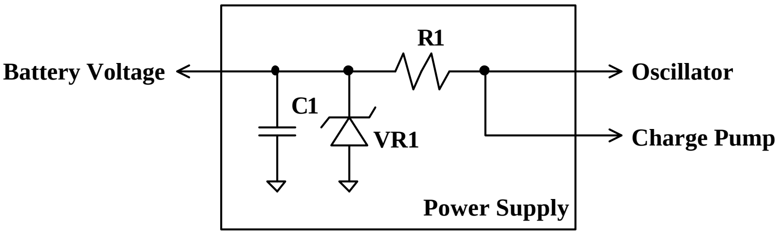

Figure 5. Schematic of power supply circuit.

The analysis is furthermore decomposed into two sub-circuit levels[8]: electrical and mechanical. The electronic portion of the WIPER architecture (Level 1), for both the solid-state and silent-relay modules, share the following relationship with mechanical components (Level 2), as shown in Figure 6. Following the analysis of interface constraints described in Appendix A.1, and applying to all sub-circuits of both solid-

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[7] The configuration of such sub-circuit is considered a standardized design with high reusability across other circuit designs.

[8] The electrical and mechanical designs, in this case, were carried out concurrently and independently of each other.

state and silent-relay WIPERs, we find that $d_{solid\text{-}state}$ and $d_{silent\text{-}relay}$ values are 9,85 and 9,94 respectively[9].

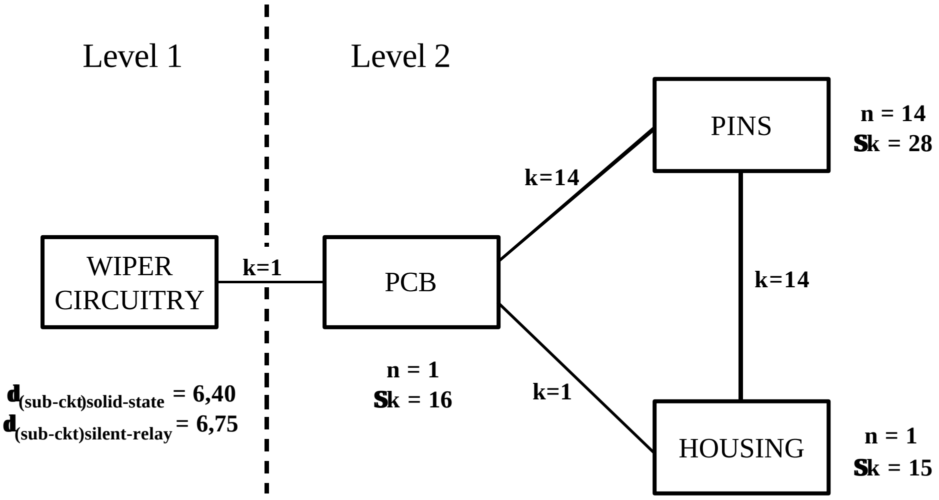

Figure 6. WIPER's relationship with other mechanical components.

The WIPER controller module requires three immediate linkages for functionality: wiper switch, wash pump, and motor. While the solid-state WIPER is only compatible with Grand Cherokee Jeeps (substitutability factor, $s = 1/3 = 0{,}33$), all three families of Jeeps (Grand Cherokee, Cherokee, and Wrangler) can use the silent-relay WIPER ($s = 3/3 = 1$). The solid-state WIPER has 60 components (N=60), of which 19 (u=19) are NTF components, yielding a NTF component ratio b of 0,317 (b=19/60=0,317). Similarly, silent-relay WIPER has 57 components with 17 NTF

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[9] For the details of computation, see (Mikkola, 2000b).

components, translating to a value of 0,298 for *b*. Now we are able to find the values for the modularization functions:

Solid-State WIPER

u = 19 components
N = 60 components
s = 0,33 components/interface
d = 9,85 interfaces/component
b = 31,7 %

$M_{solid\text{-}state}$ = 0,40

Silent-Relay WIPER

u = 17 components
N = 57 components
s = 1,00 components/interface
d = 9,94 interfaces/component
b = 29,8%

$M_{silent\text{-}relay}$ = 0,77

Graphically, the modularization functions for both WIPERs are shown in Figure 7.

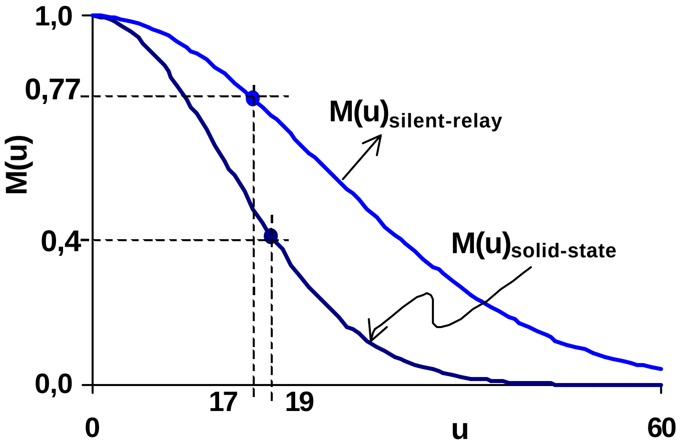

Figure 7. Modularization functions for solid-state and silent-relay WIPERs.

The silent-relay WIPER has a higher degree of modularization ($M_{silent\text{-}relay}$ = 0,77) than the solid-state WIPER ($M_{solid\text{-}state}$ = 0,4). Given the relatively similar values of interface constraints ($d_{solid\text{-}state}$ = 9,85; $d_{silent\text{-}relay}$ = 9,94), the main factor that made the silent-relay WIPER more modular is attributed to its higher substitutability factor and lower NTF component composition. Notice how the modularization gap increases as the number of NTF component increases, implying that product architectures can achieve higher levels of modularity by reducing the number of NTF components. Similarly, modularity can also be improved by designing product architectures with higher substitutability factor, if the NTF component composition remains constant.

4.2. Case B: Transmission Systems of Schindler Elevators

According to Dr. Oliver Gassmann, Head of Technology of Schindler Elevators, until the end of last century the elevators have been typical products of Utterback's (1994) 'dominant design industry'. Over capacities and cost competition dominate the market rules. The product architecture of elevators has been stable over a long period due to regulations and few innovations. In addition, the number of competitors has decreased dramatically during the last 15 years. Currently, the elevator industry is characterized by a few large and a high number of small local companies. Over 80 % of the world market share belong to the seven global players. Standardized interface specifications enable the small elevator companies to source from standard component manufacturers, and therefore benefit from economies of scale despite their small market share. Since the 1990s, there has been a strong trend towards deregulation, similar to the telecommunication industry. The induced innovation push promoted radical new solutions with new product architectures such as 'machineroomless' elevators, self-propelling cars on self-supporting structures, and advanced traffic management systems. The traditional elevator architectures (traction pull and hydraulic) account for over 90% of the market.

Based on the transmission principle, dominant elevator designs can be distinguished between: (1) the traction elevator (TR) with drive machine, ropes and counterweight, and (2) the hydraulic elevator (HY) with a hydraulic jack. According to market analysts there is a world market of 40,000 units of hydraulic elevators and 160,000 units of traction elevators worldwide per year, with a strong trend towards traction elevators. The elevator market is segmented into low-rise (less than 60 million), mid-rise (between 60 million and 200 million) and high-rise (greater than 220 million).

4.2.1. Description of the Elevator System

The research project was initiated at Schindler Lifts between 1997 and 2000, and divided in three phases. In *phase 1* a detailed analysis on two principle types of elevators (traction and hydraulic elevators) was carried out at Schindler. This analysis considered several hundred components with respective interfaces and relationships. The description and analysis were accomplished with an object modeling technique, UML (Unified Modeling Language), originally developed for supporting object oriented software development. In *phase 2*, the assessment of traction and hydraulic elevators was supplemented by several follow-up interviews with elevator experts from R&D, system management, purchasing, and marketing. The main goal of these interdisciplinary sessions was to learn about the impact of modularity on the elevator industry as a whole. Based on the vast amount of empirical data collected in phase 1 and 2, in *phase 3*, the modularization function is applied for analyzing the degree of modularization in a given product architecture. The basis of the analysis of the elevator industry is supported by the product architecture data derived from the UML analysis, which provides a comprehensive database displaying various information about the components and respective interfaces of elevator architectures in different levels of analysis.

Based on UML model, several hundreds of components with respective interfaces are documented for traction and hydraulic elevators. The UML model allows a comfortable analysis and interpretation of the product architecture on different aggregation levels. Figure 8 shows a partial product architecture of traction elevators extracted from UML model, at the highest level of analysis. The classification of components into *'unique'*, *'neutral'* and *'standard'* was done by an interdisciplinary group consisting of R&D, purchasing, and market experts. '*Unique*' represents a NTF component. '*Standard*' represents a component that is not new to the firm. '*Neutral*' can be considered as a standard component or a unique component. The linkage shared between the components is characterized as *'fundamental'* and *'optional'*. While fundamental linkages exist for all elevator variants, optional linkages are only relevant for certain variants.

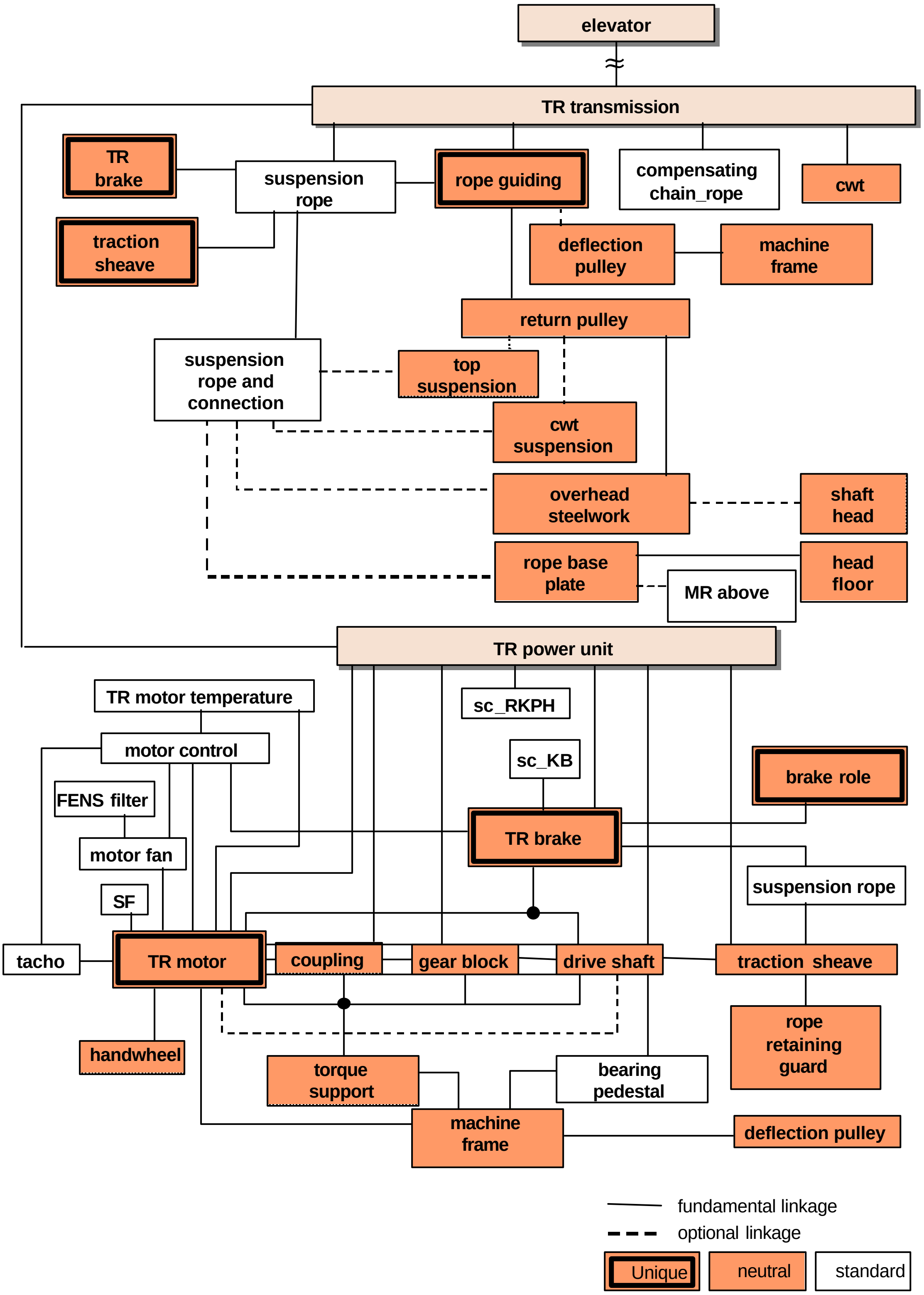

Figure 8. Partial product architecture of traction elevators (TR).

In order to illustrate how the mathematical model can be applied, the transmission sub-systems of both HY and TR elevators were selected for comparative analysis. The analysis of each elevator system is carried out at two levels: sub-system level (transmission) and system level (elevator), as shown in Figure 9.

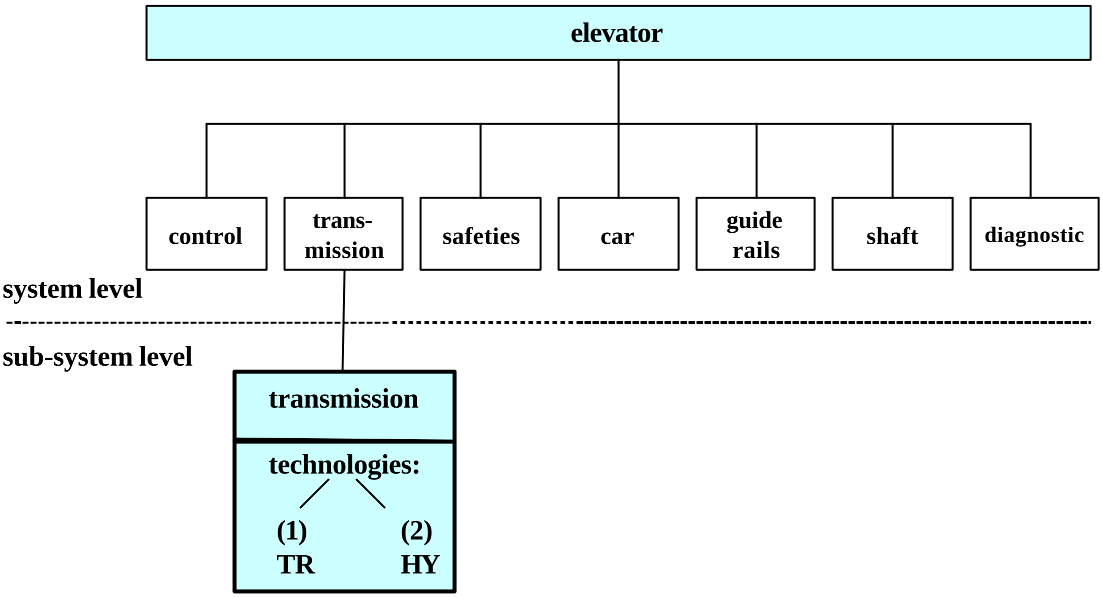

Figure 9. The elevator and its sub-systems.

The transmission sub-system, of both HY and TR elevators, is comprised of unique, neutral, and standard components with respective linkages (fundamental or optional linkages). The following assumptions are made for the sub-system level analysis:

1. For the sake of illustrating the application of the modularization function at the system level, other sub-systems (such as control, transmission, safeties, car, guide rails, shaft, diagnostic) are assumed to have the same $d_{sub\text{-}system}$ interface constraint value as the transmission sub-system. Hence, $d_{sub\text{-}system}$ represents

the average value of all sub-systems. However, a more robust analysis of the modularity should include systematic analysis of these sub-systems.

2. Substitutability factor is approximated as the number of elevator families divided by the average number of interfaces shared by the NTF components.

3. Neutral parts can be either a standard or a unique component. This assumption allows us to see the extent of impact these components, when treated as unique components, have on modularity of elevators when interfaces shared with other components remain the same.

4.2.2. Comparative Analysis of Traction and Hydraulic Elevators in terms of Modularity

Since both of these elevators have fundamental and optional linkages as well as three classification of components (unique, neutral, and standard), the basic evaluation starts with only components linked by fundamental interfaces. The maximum relationship shared among the components and respective linkages is achieved when the remaining components with optional linkages are added to the product architecture. This generates a different sets of interface constraint value d, substitutability factor s, unique component composition b, and the total number of components N in the analysis. Hence a range of modularity levels can exist for the two elevators, $M_{fundamental}(u)$ and $M(u)$ represent the basic and the maximum degree of modularity respectively. A comparative analysis of HY and TR elevators is summarized in Table 1.

Table 1. A comparison of HY and TR elevators.

HY ELEVATORS

2 families (low-rise, mid-rise)
u = 3 components
$n_{neutral}$ = 16 components

fundamental linkages	**all linkages**
N = 37 components	N = 43 components
b = 8 %	b = 7 %
s = 1,2 components/interface	s = 1,2 components/interface
d = 4,02 interfaces/component	d = 4,59 interfaces/component
$M_{fundamental}(u)$ = 0,98	$M(u)$ = 0,98
$M(u)_{u+neutral}$ = 0,36	$M(u)_{u+neutral}$ = 0,47

TR ELEVATORS

3 families (low-rise, mid-rise, high-rise)
u = 6 components
$n_{neutral}$ = 19 components

fundamental linkages	**all linkages**
N = 38 components	N = 42 components
b = 16 %	b = 14 %
s = 0,64 components/interface	s = 0,60 components/interface
d = 4,83 interfaces/component	d = 5,01 interfaces/component
$M_{fundamental}(u)$ = 0,86	$M(u)$ = 0,87
$M(u)_{u+neutral}$ = 0,07	$M(u)_{u+neutral}$ = 0,08

The graphical interpretation of modularization functions for HY and TR elevators are illustrated in Figure 10 and Figure 11, respectively.

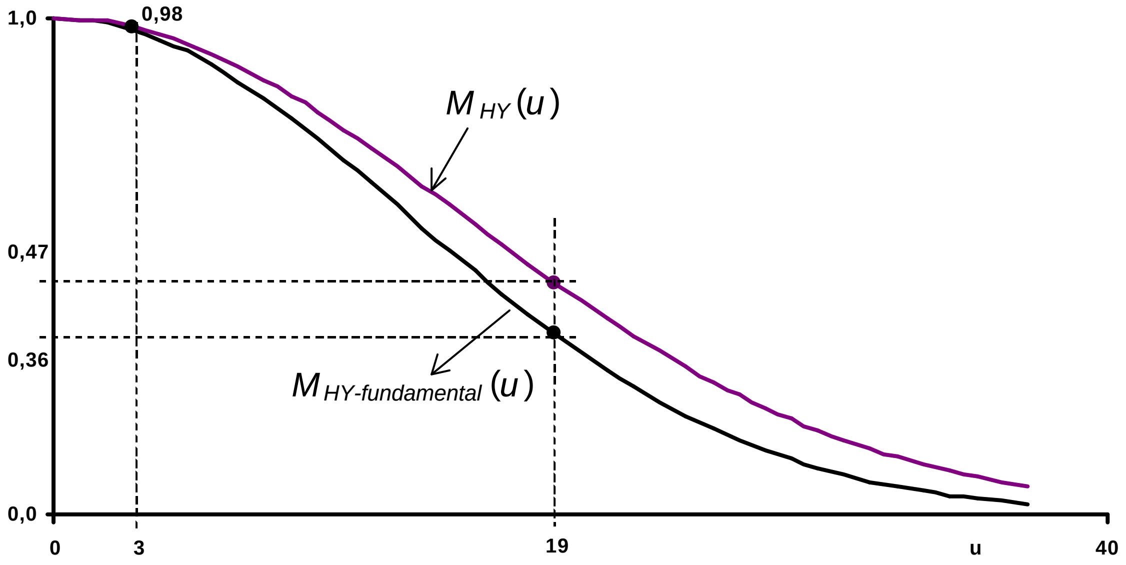

Figure 10. Modularization function of HY elevators.

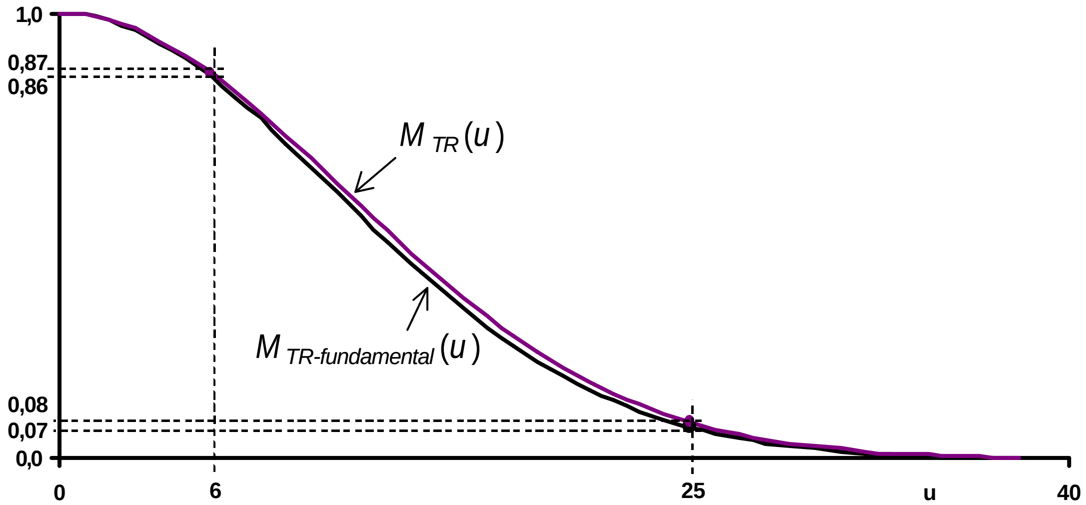

Figure 11. Modularization function of TR elevators.

Some preliminary findings of HY and TR elevators include the following:

1. Both elevators are highly modular from a unique component composition perspective, $M_{HY}(3) = 0,98$ and $M_{TR}(6) = 0,87$.

2. HY elevators are more modular than TR elevators due to higher value of substitutability factor ($s = 1,2$), lower unique component composition ($b = 7\%$), and fewer average number of interfaces shared per component ($d = 4,59$). Graphically, the higher modularity of HY elevators are indicated by the relative slopes of the modularity functions, with $M_{TR}(u)$ much steeper than $M_{HY}(u)$.

3. When neutral components are allowed to vary as unique components, then TR elevators have more leverage in gaining modularity from neutral components. For instance, TR elevator has 6 unique components and 19 neutral components. When all the neutral components are treated as unique components, then modularity value, $M_{TR}(u)$, can range from 0,08 to 0,87, compared with the $M_{HY}(u)$ range of 0,47 to 0,98.

4. The modularity of both TR and HY elevators can be increased by increasing the number of families (or models) of elevators, that is, more commonality sharing and reusability of the unique components

5. While component modularity is captured by the neutral components, the optional linkages capture interface modularity. The optional linkages between components of the HY elevators (given in the block diagram representation) provide more opportunities for modularization than the TR elevators. This is indicated by the larger differences between the modularization functions $M(u)$ and $M_{fundamental}(u)$.

6. The relative improvement in modularity can be gained by adding more components with optional linkages in the HY elevators.

5. Some Managerial and Theoretical Implications

Although the modularization function was applied to two different systems, the automobile and elevator, nevertheless, it still allowed us to analyze the degree of modularization in these systems. Some general observations are drawn from the case studies:

- Movement along the curve captures the dynamics of NTF components. Over time, when interface of NTF components becomes well specified and standardized, assuming that there are no changes are made to the product architecture, it becomes a standard component. Under these circumstances, we would observe increased degree of modularity.

- Change to a new curve indicate changes made to the product architecture in terms of adding new components, either through introduction of new innovations or through major architectural changes.

- A mature product architecture such as with the transmission systems of elevators have well understood interrelations shared among components, hence less opportunities for modularization to take place. This can be indicated by the gap between the modularization function curves, compared with those of the WIPER functions.

- The modularization function also allows us to examine the effects of architectural innovation and modular innovation when changes are made to the existing product architecture.

- The modularization function may be used as a tool for reaching consensus between the engineers and strategic managers. The systematic analysis of product architecture in terms of components, interfaces, and substitutability with respect to degree of modularity by translating their relationship in graphical form provides a common language for both the engineers and other members of the firm.

The effects and value of modularization should also be extended to include certain degree of managerial implications such as cost and benefit analysis, coordination and information management among suppliers, etc. What kinds of tools should be developed in order for managers and academics to gain a better understanding of modularization, not only in new product development, but also in organizational design, manufacturing design, marketing strategies, supply chain management, and even recycling? No doubt, the gap of knowledge sharing and interpretation between business schools and practitioners should be aligned in order to increase our understanding of modularization.

5.1. Cost implications

We can generally assume that the cost of a system with high degree of customization is higher than a product with high degree of standardization. Product architectures that use a great number of standard components (such as off-the-shelf components), often incur less cost associated with component sourcing and availability, unique manufacturing processes, and tooling costs. Cost savings are gained through economies of scale of components due to high degree of component sharing and reusability. For example, stereos systems sold by Bang & Oluffsen of Denmark are highly customized (although loaded with components from Phillips) compared to stereo systems from Sony, hence much more expensive (sometimes with a ratio of 1:3).

Costs of customized systems tends to be higher due to the integral nature of product architectures where an improvement in functional performance can not be achieved without making changes to other components. This can be prohibitively costly for complex systems such as computers, automobiles, telephones, elevators, etc. As the interfaces of the customized components become standardized, its costs are significantly reduced as changes to product architecture can be localized and made without incurring costly changes to other components, and reusability of components become possible. According to Sanchez (1999), reusability of common components within and across product lines reduces costs by reusing existing component designs, lowering costs through learning curve effects, increasing scale of component production, increasing buyer power for common components, reducing component variety and inventories, and reducing costs of product support.

5.2. Outsourcing and inter-firm learning

Modularity in product architecture design also impacts outsourcing decisions and inter-firm learning. The underlying assumption is that modular product architecture allows the decomposition of a complex system or process into smaller sub-systems. When interfaces shared among the components, modules, and sub-systems become standardized, outsourcing decisions can be made accordingly. Depending on the technological complexity and sensitivity of outsourced parts, assembler can delegate the functional specification as well as detailed engineering responsibilities to the suppliers accordingly. The outsourcing of these parts dictates the relationship and interdependence shared with suppliers, hence the differing amount of inter-firm learning gained from different product architecture approaches. In other words, the interface management of product architectures has an enormous impact on to which suppliers a component is outsourced to, how a firm should organize its knowledge stock, and how investment and resource allocation should be dealt with.

6. Conclusion and Future Research

This paper discussed modularity assessment of product architecture and its impact on substitutability and interface management. At the heart of modularity of product architectures is the relationship shared among the components and respective interfaces. It was argued that modularity takes place when interfaces shared among components in a given product architecture become specified and standardized to allow for greater substitutability of components across product families. Furthermore, certain degree complexity of modularization of product architectures can be captured with the composition of new-to-the-firm (NTF) components and how these components are linked to the rest of the components. The relationships shared among NTF components and standard components define the degree of modularity of a given product architecture, assuming that any product architecture range from being perfect modular (no NTF components) to being perfect integral (no standard components). Substitutability factor also plays an important role in the degree of modularization of product architectures, as they are a function of the number of product families made possible by the modular components as well as the number o f interfaces required for functionality.

A simple mathematical model, termed modularization function, was applied for analyzing modularity by taking into account the following variables: number of components, number of interfaces, and substitutability factor. In order to illustrate how this model can be used, two distinct technological systems were analyzed for comparison: (1) Chrysler Jeeps windshield wipers controllers (WIPER) and (2) transmission systems of Schindler Elevators.

In the WIPER case, the modularization analysis showed that silent-relay product architecture had a higher degree of modularization compared with the solid-state architecture due to its higher substitutability factor and lower NTF composition. The analysis of the traction pull (TR) and hydraulic (HY) transmissions of Schindler elevators, on the other hand, indicated that both systems are quite modular from a component composition perspective. However, from a substitutability perspective, TR elevators are more modular than HY elevators. Although the application of the mathematical model to these two distinct systems provide very preliminary findings on how degree of modularity of product architectures can be assessed, nevertheless it can be used as powerful tool for theoretically analyze how components, interfaces and substitutability factor impacts modularity. We could analyze, for instance, the implications of NTF components (such as outsourcing) in dynamics of modularity in product architectures over time, which will be indicated by a movement along the curve.

In order for the model to have strategic value, managerial implications to cost and benefit analysis should be taken into consideration as well. Furthermore, as the majority of products sold in the market place involve many suppliers with distinctive knowledge and expertise, the design of product architectures should also take into consideration how it impacts the organizational design of NPD tasks vis-à-vis manufacturing design and inter- versus intra-firm learning and knowledge management. Moreover, it has been debated that outsourcing of non-core technical activities are enabled by the standardization of these non-core components with respect to the core technology. Can decisions regarding to product architecture designs provide us insights to strategic decisions regarding outsourcing, manufacturing, and supply chain management? If so, how should firms design its organization to match such strategies with respect to its suppliers and customers? Other areas of great interest for research include, for example, the impacts of product architecture design choices (e.g., multiplexing and de-integration of components) with respect to postponement and mass customization strategies.

APPENDIX A - MODULARIZATION FUNCTION FORMULATION

The NTF component composition of a given product architecture, *b*, can be represented by:

$$b = \frac{n_{NTF}}{N} = \frac{u}{N} \quad ; \quad 0 \leq \mathrm{b} \leq 1 \quad \text{Equation A.1.}$$

$b = 0$ represents a perfect-modular product architecture

$b = 1$ represents a perfect-integral product architecture

Given the range of component composition defined by Equation A.1., it is reasonable to assume that there is a relationship between modularization and the number of NTF components. In other words, it is expected that the degree of modularization, *M*, decreases at a rate, *r*, that is proportional to the amount of modularization present with each set of NTF components, *u*. If *M* is amount of modularization present in a given product architecture with any set of NTF components *u*, then as the number of NTF components vary, the amount of modularization will have changed by the amount of $\Delta M{=}rM$. In other words, for any unit change of NTF components ($\Delta u{=}1$), the corresponding amount of modularization change ΔM is proportional to the initial amount of modularization. From this, it seems plausible that a similar relation should hold for the decrease in any the amount of modularization in any set of NTF components; that is, the decrease of modularization should be proportional to the change in the number of NTF components as well as the initial amount of modularization.

$$\Delta M = (-rM)\Delta u \qquad \text{or} \qquad \frac{\Delta M}{\Delta u} = -rM$$

The factor r is the NTF component ratio per the total interface constraints in a given product architecture. Since a given product architecture may generate many family variations, the interface constraint factor is magnified by substitutability factor, s.

Thus, the factor r is represented as:

$$r = \frac{b}{sd} = \frac{u / N}{sd} \qquad \text{Equation A.2}$$

Thus,

$$\Delta M = (-rM)\Delta u = \left(-\frac{u / N}{sd} \right) M \Delta u$$

In differential equation form,

$$\frac{dM}{du} = -\frac{u}{Nsd} M \qquad \text{or} \qquad \frac{dM}{M} = -\frac{u}{Nsd} du$$

For any constant r, the solutions to the above differential equation are of the form:

$$M(u) = M_0 e^{-u^2/2Nsd}$$

It is assumed that the amount of modularization is constraint by interface compatibility factors introduced by the NTF components in a given product architecture, thus the amount of modularization M in a perfect modular product architecture is when there are no NTF components (u=0), hence the initial condition of $M(0) = M_0 = 1.0$.

Consequently, the modularization function is represented as:

$$M(u) = e^{-u^2/2Nsd} \qquad \text{Equation A.3.}$$

A.1. Formulation of Interface Constraint Factor, $\mathbf{d}$

Interface constraints of a given product architecture are estimated in terms of the number of interfaces shared per component, interfaces shared per module, or interfaces shared per sub-system. Although there are many ways of representing the relationship between number of components and respective interfaces, here I simply approximate it as the ratio of the total number of interfaces per the number of components in a sub-system of a given product architecture:

$$d_i = \frac{\sum k_c}{n_c}$$

As product architectures have multiple sub-systems, the aggregate value for all interface constraints from these sub-systems, $d_{sub\text{-}system}$, can be approximated as the average of all d_i, that is,

$$d_{sub-system} = d_{average} = \frac{\sum_{i=1}^{I} d_i}{I}$$

I = number of sub-systems (or sub-circuits)

In cases when additional decomposition within a sub-circuit is possible (as the WIPER case), then we would also expect additional interface constraints shared among interfaces of the sub-circuits. In this case, then the aggregate δ value of the black box (e.g., module or sub-system) should also include the additional δ value created among circuits.

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