Managing Modularity of Product Architectures: Toward an Integrated Theory

Juliana Hsuan Mikkola, *Member, IEEE*, and Oliver Gassmann

***Abstract*—The management of innovation through modular product architecture strategies is gaining increasing importance for firms, both in practice and theory. Modularity refers to a new product development strategy in which interfaces shared among components in a given product architecture are specified and standardized to allow for greater substitutability of components across product families. It is argued that the degree of modularity inherent in product architectures depends on the constituent components and interfaces. This paper introduces a mathematical model, termed the modularization function, for analyzing the degree of modularity in a given product architecture. It takes into account the following variables: components; degree of coupling; and substitutability of new-to-the-firm components. The application of the modularization function is illustrated with two elevator systems from Schindler—traction and hydraulic. The comparative analysis of the elevators 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).**

***Index Terms*—Components, degree of coupling, interfaces, modularity, new product development (NPD), product architecture, substitutability.**

I. INTRODUCTION

INTERNATIONALIZATION of markets, deregulation, more demanding customers, and advances in information and transportation technology have contributed to the complexity of managing new product development (NPD), manufacturing activities, and supply chains [4], [15], [16], [21], [22], [25], [36], [52]. More and more firms (e.g., in consumer electronics, automotive, and elevator industries) are facing difficulties in managing increasing product variety and model mix [54]. A challenge for these firms is to find ways to replace products and occasionally, to expand product lines with innovative, high-quality models that minimize development and production costs [10]. Many firms are pursuing modular product architecture design strategies in order to shorten NPD lead time, to introduce multiple product models quickly with new product variants at reduced costs, and to introduce many successive versions of the same product line with increased performance levels.

In the broadest terms, *modularity* is an approach for organizing complex products and processes efficiently [2] by decomposing complex tasks into simpler activities so they can be managed independently. Modularity permits components to be produced separately and used interchangeably in different product configurations without compromising system integrity [2], [15], [18]–[20]. It intentionally creates a high-degree independence or a "loose coupling" [34] between component designs by standardizing component interface specifications [41]. Modularity is made possible by partitioning information into visible design rules and hidden design parameters [2], and by standardizing interfaces to allow component variations to be substituted into product architectures [41]. The relationship among components and their respective interfaces is at the heart of product architectures. The degree of modularity is dependent on the extent of: 1) economies of substitution of components across product families [19], [20]; 2) disaggregating and recombining the system into new configurations, or mixing-and-matching [19], [41], [43]; and 3) a system achieving greater functionality through components being specific to one another [43].

Similar systems produced by different companies undoubtedly have different product architecture designs due to different design and technology choices. This suggests that the composition of components is idiosyncratic to a particular product architecture design. A firm's ability to develop and manufacture new products (either customized or standardized) is largely contingent on both the firm's NPD strategy and how its relationship with suppliers and customers is nurtured over time. For instance, Clark and Fujimoto [7] found that Japanese cars used a higher percentage of unique components than American cars did. This strategy is reflected by the Japanese companies' policy of subcontracting much of their component design function to component suppliers, while maintaining enough flexibility in their assembly plants to support high levels of product variety.

Variation in product configurations are rooted in product architectures, while the way in which components can be disaggregated and recombined into new configurations (without losing functionality and performance) is based on the level of modularization in product architectures. The constituent components, which can be standard or new-to-the-firm (NTF), and how they are linked to one another, determine the performance and cost benefits of product architectures. According to Sanderson and Uzumeri [42], using standard parts can save on design effort and, thus, reduce costs, but new products may require that new parts be designed. The development of new parts may incorporate technology that is new to the firm and require long development lead times and significant investment.

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J. H. Mikkola is with the Department of Operations Management, Copenhagen Business School, Frederiksberg DK-2000, Denmark (e-mail: jh.om@cbs.dk).

O. Gassmann is with the Institute for Technology Management, University of St. Gallen, St. Gallen CH-9000, Switzerland (e-mail: Oliver.Gassmann@unisg.ch).

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Component selection embedded in product architectures reflects different strategic choices made by firms. In computer workstations, Sun Microsystems emphasizes off-the-shelf parts relative to its primary competitor, Apollo Computer [3]. Notebook computers, on the other hand, contain more product specific components [47] than desktop computers, although both products perform essentially the same function, are produced in similar volumes, and employ similar component technologies [55]. If a firm is to invest time and money to develop new components for product architectures, what are some alternatives to increase the value of these components? To what extent do choices of components and respective interfaces influence the modularity of product architectures? How sensitive is product architecture modularity to changes in component composition? How can we systematically assess the complexities of modularization induced by components and respective interfaces embedded in architectural designs?

In order to provide a first step to address these questions, a mathematical model is derived for analyzing the degree of product architecture modularity by taking into consideration the following variables: number of components, degree of coupling, and the substitutability of NTF components. The modularization function is illustrated with two elevator systems from Schidler Lifts, the second largest elevator corporation in the world. The remainder of the paper is organized as follows. The next section presents a theoretical foundation for modularity and product architecture through a comprehensive literature review. This includes a brief discussion on the effects of components, interfaces, degree of coupling, and substitutability of NTF components as key factors in product architecture modularity. Section IV introduces a modularization function for describing the level of modularization as a function of the key factors along with the assumptions made for formulating the function. Section V applies the modularization function to two product architectures of Schindler elevators: traction and hydraulic. The paper concludes with a discussion on generalization and limitations of the modularization function, managerial implications for the elevator industry, and suggestions for future research.

II. OVERVIEW

Product configurations are rooted in product architecture designs, which may be integral or modular. In assessing modularity of product architectures, issues regarding decomposability (i.e., modularization) as well as bundling of disparate components into a new innovation (i.e., integration[1]) should be taken into consideration. Firms need to understand the fundamental relationships shared between components, respective interfaces, and substitutability of newly developed components embedded in product architectures. The literature review will reveal that there are few quantitative metrics available to measure modularity. In this paper, the aim is to take a first step in proposing a function which can be used to measure the level of modularity in a product architecture as a function of components, interfaces, degree of coupling, and substitutability in which modularity plays a special strategic role for firms. We present a methodology that provides a measure of modularity aimed at helping management understand strategic and new product design implications for product architecture designs.

Many studies on modularity are qualitative and exploratory in nature (cf. [2], [5], [19], [25], [28], [37], and [41]). The few quantitative studies typically apply optimization models to address manufacturing issues (cf. [1], [12]–[14], [35], and 7[38]). Although these studies have contributed greatly to our understanding of modularity, they offer limited insights into how firms measure the degree of modularity embedded in product architectures. Nevertheless, Table I lists several studies that focus on measuring modularity.

These studies support and complement our approach, specifically by extracting information from bill-of-materials (BOM) to measure component standardization [8], [9], [49], examining the variation in component sharing [17], designing product specific components [47], and estimating the impact of design alternatives [50]. Our work seeks to integrate these approaches (in addition to key concepts mentioned in the qualitative studies) by helping to gain a better understanding of the effects of the following elements of product architectures on modularization: components and respective interfaces; degree of coupling; and substitutability (Table II). We are unaware of previous studies that combine these elements to assess the degree of modularity in product architectures. We take a first step to unifying the literature on product modularity by proposing a function that seeks to integrate all these factors into a single measure representing the level of modularity.

III. PRODUCT ARCHITECTURE

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 how they interface with the rest of the device [46], [48]. Depending on the interdependencies shared between components and respective interfaces, product architectures can vary from integral to modular.

In integral product architectures, a one-to-one mapping between functional elements and physical components of a product is nonexistent, and interfaces shared between the components are coupled [46], or highly interdependent. Changes to one component cannot be made without making changes to other components. Integral architecture designs enhance knowledge sharing and interactive learning as team members rely on each other's expertise. Integral architectures are designed with maximum performance in mind, and the implementation of functional elements may be distributed across multiple physical elements [48]. For example, Apollo Computer of the 1980s was more integral than IBM PCs or Sun Microsystems. High performance was emphasized and the workstation was designed with a proprietary architecture based on Apollo's own operating and network management systems. Much of the hardware was designed in-house. Apollo's designers believed

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[1] Part integration is a common motive for integral product architectures [48], [50], and refers to [47, p. 647]: "the combination of multiple parts into one contiguous part. [It] minimizes the use of material and space associated with component interfaces, and may improve geometric precision, but compromises the one-to-one mapping from functional elements to components."

TABLE I
LITERATURE ON MEASUREMENT OF MODULARITY

Authors	Purpose	Approach and Method
Ulrich & Pearson [49]	• To measure the *manufacturing content* - the attributes of the design that drive cost	• Product archeology - an approach to gather objective data for product development research. Case study: coffee makers
Ulrich et al. [50]	• To estimate the impact of different design alternatives on the net economic benefit of a product	• Economic model to illustrate the relationships among DFM, lead time, and profits. Case study: Polaroid camera
Fisher et al. [17]	• To examine variation in component sharing practice and to identify factors that can explain the variation	• Mathematical model (complemented with optimization, simulation, and regression analyses). Case study: automotive breaking systems
Ulrich & Ellison [47]	• To develop a theory to explain when a firm can benefit from designing product-specific components	• Regression analysis based on survey on engineered, assembled goods. Validation: hypothesis testing with a cross-sectional analysis of 225 products
Collier [8], [9]	• To measure the effect of component standardization on aggregate safety stock levels and service levels	• An analytical measure of product structure termed 'the degree of commonality index'. Tested with simulation experiment

that it was necessary for various parts of the design to be highly interdependent for achieving high levels of performance in the final product [2].

Contrary to integral product architectures, modular product architectures [28], [41], [48] are used as flexible platforms for leveraging a large number of product variations [23], [26], [31], [37], [39], [40]. These enable a firm to gain cost savings through economies of scale from component commonality, inventory and logistics, as well as to introduce technologically improved products more rapidly. Modular architectures enable firms to minimize the physical changes required to achieve a functional change. Product variants often are achieved through modular product architectures where changes in one component do not lead to changes in other components, and physical changes can be more easily varied without adding tremendous complexity to the manufacturing system. Unlike the Apollo Computer, Sun Microsystems relied on a simplified, nonproprietary architecture built mainly with off-the-shelf hardware and software, including the widely available UNIX system. Two proprietary modules were developed in-house to link the microprocessor efficiently to the workstation's internal memory. However, only using two proprietary components was not enough to lock Sun's customers into its own proprietary operating system or network protocols as they were easily copied and could not be patented [2]. Some tradeoffs between modular and integral designs are listed in Table III.

A. Components

A *component* is defined as a physically distinct portion of the product that embodies a core design concept [6] and performs a well-defined function [24]. Product architecture defines the way in which components interact with each other. There are many ways of categorizing components, depending on the purpose of the study. Similar to Ulrich and Pearson [49], we also analyze degree of modularity through direct observations of the product architectures and their constituent parts. In our methodology, product architectures are disassembled into distinct components so that BOM (which is both firm and product specific) is generated. The component attributes (i.e., total number of components, component description, and component unit costs) can be observed from the BOM. We wish to use component information that is present in BOMs because one purpose of our model

TABLE II
ELEMENTS OF PRODUCT ARCHITECTURE

Elements of Product Architecture Modularity	**Managerial Implications**
Standard components	• Economies of scale • Cost savings • Specialization • Development of capabilities • Standardized interface specifications
NTF components	• Technological risk • Product novelty • Superior performance • Limited imitation • Long NPD lead time • Non-standardized interface specifications
Degree of coupling	• Synergistic specificity • Identification of critical components • Tightness of coupling among components
Substitutability	• Economies of substitution • Component sharing • Product variety • Upgradability

is to capture the implication of new-to-the-firm (NTF) components (whether produced by the firm or by the supplier) for existing product architectures. In our analysis, we find it useful to divide components into two categories: 1) standard and 2) NTF, depending on whether the firms have had prior knowledge and application of these components in previous or existing product architectures. The selection of components reflects strategic choices made by firms.

1) Standard Components: Standard components refer to components that have been used in previous or existing architectural designs by the firm (i.e., carried over components) or components that are available from firm's library of components (i.e., qualified components). A subset of standard components is the commodity components, which are often off-the-shelf or generic parts. These components have well-defined technical specifications that are generally accepted as industry standards, as many suppliers produce these components. These parts are often listed in catalogues with unit prices varying accordingly with the volume purchased. Due to previous experience with standard components, possible interface compatibility issues with other components can be assessed quickly without incurring expensive testing costs. According to Ulrich and Ellison [47], some benefits for firms to select an existing component include: 1) to minimize investment—the reuse of existing components avoids significant additional investment in product development and tooling; 2) to exploit economies of scale from production volume; and 3) to preserve organizational focus leading to specialization and the development of capabilities.

2) NTF Components: NTF components, on the other hand, refer to product-specific components [47] that are introduced to the firm for the first time, such as with modular innovations.[2] Since prior knowledge about how NTF components interact with other components is limited, NTF components are assumed to contain higher technological risks than standard components. Interface compatibility issues with other components within the product architecture have to be tested and re-evaluated regularly, and sometimes this process can be costly and time consuming.[3] 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, thus creating competitive advantages for the firm, at least in the short run. However, too many NTF components may delay product development lead time and increase the technological complexity of the product architecture, as the system achieves greater functionality by the strong interdependence shared among components, or high-synergistic specificity [43]. Examples of NTF components in Schindler's traction elevators include rope guiding, traction sheave, traction motor, traction brakes, and brake role.

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[2] Modular innovations are innovations that change only the relationships between core design concepts of a technology without changing the product's architecture [24]. It refers to the introduction of new component technology inserted within an essentially unchanged product architecture [5].

[3] In a study of multiproject management in the automobile industry, Cusumano and Nobeoka [10] found that developing components new to the firm requires extra time for concept generation, producing prototypes, and testing that companies can not do in parallel, hence, requiring both a longer lead time and more engineering hours.

TABLE III
TRADEOFFS BETWEEN MODULAR AND INTEGRAL PRODUCT ARCHITECTURE DESIGNS

Benefits of Modular Designs	***Benefits of Integral Designs***
• Task specialization • Platform flexibility • Increased number of product variants • Economies of scale in component commonality • Cost savings in inventory and logistics • Lower life cycle costs through easy maintenance • Shorter product life cycles through incremental improvements such as upgrade, add-ons and adaptations • Flexibility in component reuse • Independent product development • Outsourcing • System reliability due to high production volume and experience curve	• Interactive learning • High levels of performance through proprietary technologies • Systemic innovations • Superior access to information • Protection of innovation from imitation • High entry barriers for component suppliers • Craftsmanship
Examples: Elevators, passenger cars, IBM PCs, Lego toys	***Examples:*** Formula One cars, Apollo Computers, satellites

When faced with the tasks of developing a new component, a firm can choose either to design and to manufacture it in-house or outsource these tasks to supplier(s). Similar to Ulrich and Ellison [47], we also do not address the question of *who* designs these components, rather, that a component is designed by someone specifically for use in the firm's product architectures. Designing NTF components allows firms to: 1) maximize product performance with respect to holistic customer requirements, that is, requirements that arise in a complex way from most of the components of a product; 2) minimize the size and mass of a product—the desire for part integration in order to conserve mass and size gives rise to an integral architecture which implies that components will have to be redesigned; and 3) minimize the variable costs of production—variables are largely determined by component mass and size.

Ulrich and Ellison [47] measure the degree to which components are designed for a specific product by weighting the relative share of components designated specifically for the product, carried over from a previous product, and modified for the product by a supplier. Instead of assigning weights to component categories, we calculate the percentage of NTF components (i.e., product-specific components) obtained from the BOM

$$b = \frac{n_{\mathrm{NTF}}}{N} = \frac{u}{N}; \qquad 0 \leq b \leq 1$$

where

u number of NTF components;
N total number of components;
N $-u$ number of standard components.

Variable b allows us to represent the component composition of the product architecture[4] from a perfect modular architecture ($b = 0$) to a perfect integral architecture ($b = 1$).

B. Interfaces

Interfaces are linkages shared among components, and interface specifications define the protocol for the fundamental

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[4] Cusumano and Nobeoka [11] also use the percentage of unique components as a key variable for assessing project scope. Unique components refer to components that a manufacturer designs from scratch in-house for a given model, as opposed to reusing components from other models or the immediate predecessor of a new model. In our model, the variable b does not distinguish between unique components that are developed in-house or by a supplier.

interactions across all components comprising a technological system. Modularity intentionally creates a high degree of independence between component designs by standardizing component interface specifications[5] [41]. Furthermore, the formalization and development of interface specifications has a tremendous impact on setting worldwide industry standards [27], [44].

The degree to which interfaces are standardized and specified defines the compatibility between components. Standard components have well specified and standardized interfaces, hence product architectures composed of standard components are assumed to be modular. Conversely, interface specifications, and hence, interface compatibility issues of NTF components with other components of a given product architecture are not well understood. Consequently, the introduction of NTF components into product architectures hinders modularity freedom. Interface specification of NTF components is dependent on the amount of technological innovation available in the market. For instance, if the NTF component is new to the industry, its interface specification is most likely to be ill specified. However, when the NTF component is new only to the firm, its interface specification is generally well defined within the industry, but not standardized within the firm. Only when the interface specification of NTF components becomes well specified and standardized within the firm does a NTF component becomes a standard component. According to Ulrich [46], standardization arises when: 1) a component implements commonly useful functions and 2) the interface to the component is identical across more than one product.

C. Degree of Coupling

The product performance is governed by many component parameters that are related to one another in a complex, interdependent fashion. Components are typically characterized by many design parameters, which may need to be refined arbitrarily in order to maximize overall product performance [47]. The way in which components are linked with one another creates a certain degree of coupling. A component that depends on interfacing with many components for functionality imposes a high degree of coupling. For example, a microprocessor, which is a component in a motherboard, which is, in turn, a PC subsystem, would be considered a critical part based on the number of interfaces shared with other components. For a microprocessor to function properly, it has to interface directly with a number of components, ranging easily from 56 to over 200 interfaces. Conversely, a capacitor would present a lower degree of coupling than microprocessors. Typically, capacitors require two interfaces for functionality, a cathode and an anode.

A product architecture with a high percentage of critical components may not be easily decomposed. In Schilling's [43] terms, product architectures with a high degree of coupling among the components exhibit high "synergistic specificity" as the strong interdependence shared among components inhibits recombination, separability, and substitution of components. This prevents the architecture from shifting into a more modular one. We estimate the degree of coupling [δ] as the ratio of the number of interfaces [k] per component [n] in a subsystem of a given product architecture. The empirical information on the number of interfaces can be gathered from product architecture schematics where specific linkages among components are laid out[6]

$$\delta_i = \frac{\text{total number of interfaces in subsystem } i}{\text{number of components in subsystem } i} = \frac{\sum k_c}{n_c}.$$

For product architectures with multiple subsystems, the aggregate value of δ for these subsystems, $\delta_{\text{subsystem}}$, can be approximated as the average of all δ_i, that is

$$\delta_{\text{subsystem}} = \delta_{\text{average}} = \frac{\sum_{i=1}^{I} \delta_i}{I}$$

$$I = \text{ number of subsystems.}$$

D. Substitutability

Another crucial element of product architecture modularity is substitutability. Garud and Kumaraswamy [20] use 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. Economies of substitution [19] exist when the cost of designing a high-performance system through the partial retention of existing components is lower than designing the system afresh. While standard components facilitate component reusability, NTF components improve the technological performance of the upgraded product architecture. The challenge is to design product architectures with a desirable combination of standard and NTF components to gain from economies of substitution.

An aspect of substitutability is component sharing (i.e., using the same version of a component across multiple products) which is a product-based strategy based on the premise that families of similar products have similar components [17]. Component sharing is viewed by firms as a way to offer high variety in the market place while retaining low variety in their operations. Component sharing of NTF components is especially critical. As articulated by Fisher *et al.* [17, p.299]: "Because each new and unique component must be designed and tested, component sharing can reduce the cost of product development. Each new and unique component generally also requires an investment in tooling or other fixed costs of production. Therefore component sharing may also reduce the required production investment associated with a new product." The managerial challenge is how to provide the high degree of uniqueness that seems necessary for competitive success while retaining the scale economies required for low cost. Firms generally do not introduce radical product designs to the market every time a new product is introduced. Incremental product designs are observed more often. We would imagine

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[5] Sanchez [40] furthermore classify seven different types of interfaces—attachment, spatial, transfer, control and communication, environmental, ambient, and user interfaces. For interface discussions on software platform designs, see [29].

[6] The analysis of data from BOM and schematic drawings is very similar to Ulrich and Pearson's product archeology approach [49], in which objective data is gathered from actual physical products

that a firm saves costs by using standard components in product architecture designs, than if it were to use NTF components. If a firm is to invest the time and effort to incorporate NTF components into the product design, the value for using these components are often justified by their superior performance. If cost savings and shorter NPD lead time are the performance criteria, then the cost savings of incorporating NTF components into incremental product designs can be justified by sharing the same component design across product families.

The impact of substitutability of NTF components in product architecture modularity is captured through the "substitutability factor" [s], which is estimated as the number of product families made possible by the average number of interfaces of NTF components [k_{NTF}] required for functionality

$$s = \frac{\text{no. of product families}}{k_{\mathrm{NTF}}\ \text{(avg)}} = \frac{\sum_{j=1}^{L} PF_j}{\frac{\sum_{i=1}^{K} k_{\mathrm{NTF}}}{K}}$$

where

L	number of product families;
K	total number of interfaces of NTF components.

For example, if an NTF component can be used in ten families (or ten times the same component), and two interfaces must be shared for functionality, then the substitutability factor of the product architecture is five components per interface. The greater the number of families that can use the NTF component, the higher the substitutability factor, hence the higher degree of product architecture modularity.

IV. MODULARIZATION FUNCTION

A simple mathematical model, termed the modularization function $M(u)$, is derived to measure the degree of modularity in a given product architecture as a function of the following variables: components [N and u], degree of coupling [δ], and substitutability factor [s], as shown in (4.1). (refer to the Appendix for the formulation and derivation of the modularization function)[7]

$$M(u) = e^{-u^2/2Ns\delta}. \tag{4.1}$$

The sensitivity relationship of the modularization function $M(u)$ with respect to the NTF component composition, u, is expressed as follows:

$$S_u^M = \frac{u}{M} \cdot \frac{dM}{du} = -\frac{u^2}{Ns\delta} \tag{4.2}$$

where

$M(u)$	modularization function;
S_u^M	sensitivity function;
u	number of NTF components;
N	total number of components;
s	substitutability factor;
δ	degree of coupling.

The modularization function assumes that the combined effect of the variables varies exponentially with any set of NTF components. Every time the component composition b is altered (such as with incremental innovations) the degree of modularity also varies. In many cases, the introduction of NTF components requires changes to other parts of the product architecture as well, hence changing the values of N and δ. If we simply assessed the degree of modularity based on the number of components (whether standard or NTF) and ignored the effects of interfaces (captured in δ and s) we may overlook the impact of interfaces on product architecture modularity.

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

1) The functional specifications of components, including interface specifications, do not change over a period of time. This assumption allows the evaluation of the architecture's configuration and components composition independently from other subsystems.
2) The product architecture comprises a combination of standard and NTF components. Since the competitors can easily copy product architectures comprised entirely of standard components, it is assumed that there should be some amount of NTF components in the product architecture.
3) NTF components impose higher technological risks and greater interface compatibility issues with other components within the product architecture. Therefore, the NTF components composition in a product architecture should vary inversely with the degree of modularity.
4) All standard components, NTF component, and interfaces (i.e., electrical, logical, physical, etc.) are equally critical.

The modularization function captures the complexity of product architecture designs that are often firm specific. It is one way of interpreting modularity of product architectures objectively. Although the information required for the assessment is often proprietary (especially with respect to NTF components), it is widely available within the firm (i.e., in databases, BOMs, schematic drawings, etc.). Both academic researchers and practitioners can gain valuable insights from the modularization function. For researchers, simulations such as sensitivity, optimization, tradeoff, and scenario analyses on different product architectures can be performed. Two distinct product architectures may have similar $M(u)$ values, but it does not necessarily mean that they are equally modular. It may mean that one product architecture is more tightly coupled than the other (higher δ), or has higher substitutability of NTF components (higher s), or simply having lower number of NTF components (smaller u). The model enables researchers to theoretically test causal linkages of the variables, as they shape the product architectures to become more modular (or integral). For practitioners, the modularization function may help managers to analyze various managerial and strategic implications of architecture design decisions (Table II), which are usually bounded to the firm's vision, influenced by strategic managers' knowledge and expertise about the technological developments in the industry. When fundamental relationships between the variables are analyzed objectively, it can help

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[7] The modularization function was originally derived to analyze product architectures of Chrysler Jeeps windshield wipers controllers. For preliminary findings, see [32].

managers to understand and foresee the impacts of system decomposition into simpler portions (or integration of standardized components into a new innovation) on the degree of modularity in next generation of product architectures. Changes in product architecture designs call for different strategies for managing production volume, manufacturing processes, amount of product variety, concurrent engineering, advertisement, etc. When the systematic analysis of product architectures can be illustrated graphically, it enhances knowledge sharing while facilitating consensus making between engineering and management. It may also be used as a tool for analyzing competitors' product architectures through reverse engineering. This exercise often not only reveals the potential future technological innovation pursued by the competitors, it also reflects on their current product architecture strategies and manufacturing capabilities. For the remainder of the paper, we illustrate how the function is applied to two different product architectures from Schindler elevators; namely traction pull and hydraulic transmission based elevators.

V. ROLE OF MODULARITY IN THE ELEVATOR INDUSTRY

Until the end of 1900s, elevators had been characterized as typical products within Utterback's [51] framework of dominant design. According to the elevator experts from Schindler Lifts, over capacities and cost competition has dominated the current market scene.[8] The product architecture of elevators has been stable over a long period due to regulations and relatively few innovations. The number of competitors has also decreased dramatically during the last 15 years. Currently, a few large companies plus many small local companies shape the elevator industry. Over 80% of the world market share belongs to seven global players. Modularity though standardized component interfaces has enabled smaller elevator companies to source from standard component manufacturers and, therefore, to benefit from economies of scale notwithstanding their small market share. Since the 1990s, there has been a strong trend toward deregulation, similar to that which has been taking place with the telecommunication industry. The induced innovation push has promoted radical new solutions with new product architectures such as "machineroomless" elevators, self-propelling cars on self-supporting structures, and advanced traffic management systems.

In our study, we concentrate on analyzing the traditional elevator architectures and related component innovations, accounting for over 90% of the market. Dominant elevator designs are: 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 at Schindler Lifts, the world market for Schindler designs is 40 000 units of HY elevators and 160 000 units of TR elevators per year, with an increasing trend toward TR elevators. In general, the elevator market is segmented into low-rise (less than 60 000 units), mid-rise (between 60 000 and 200 000 units), and high-rise (greater than 220 000 units).

A. Data Collection and Analysis

Data were collected at Schindler Lifts from 1997 to 2000, divided into three phases. In *Phase 1* a detailed analysis was carried out. The description and analysis of TR and HY elevators were accomplished with an object modeling technique called unified modeling language (UML), originally developed for supporting object-oriented software development. All components and respective interfaces of elevator architectures at different aggregate levels of analysis were mapped and recorded into a database using UML. In *Phase 2,* the assessment of TR and HY 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, and to verify that our assumptions and interpretation of the data are accurate. Then, in *Phase 3,* the modularization function [(4.1)] and sensitivity function [(4.2)] were applied for analyzing the degree of modularization in TR and HY elevators.

B. Comparative Analysis of Traction and Hydraulic Elevators

The basis for the analysis of the HY and TR elevators is supported by the product architecture data derived from the database using UML. To illustrate the modularization function, we selected the transmission subsystems of both HY and TR elevators for a comparative analysis. The elevator systems were analyzed at both the subsystem level (transmission) and the system level (elevator), as shown in Fig. 1.

We then decomposed the product architecture into subunits, so that each one of the subunits can be assessed independently. Fig. 2 shows a partial product architecture of TR elevators. The classification of components into "*unique*," "*neutral*," and "*standard*" was defined by an interdisciplinary group of R&D, purchasing, and market experts. "*Unique*" represents a NTF component.[9] "*Standard*" represents a component that is not new to the firm. Depending on the application and customization requested by the customers, a "*neutral*" component can be considered either as a standard component or as a unique component. The linkage (or interface) 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.

We sum the number of standard, neutral, and unique components to obtain the total number of components N. The next step is to assess the substitutability factor of the TR or HY transmission product architectures, which is approximated by the number of elevator families divided by the average number of interfaces shared by the NTF components comprising each transmission subsystem.

In counting the number of components, the neutral components posed difficulties because these components are considered unique components by some customized elevators but not others. For instance, the deflection pulley is a neutral component that is linked to the machine frame with a fundamental linkage. In some TR elevator applications, these components are unique

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[8] The information presented in this section is based on interviews with various experts from the elevator industry.

[9] In order to be consistent with Schindler's terminology for components, unique components are similar to NTF components.

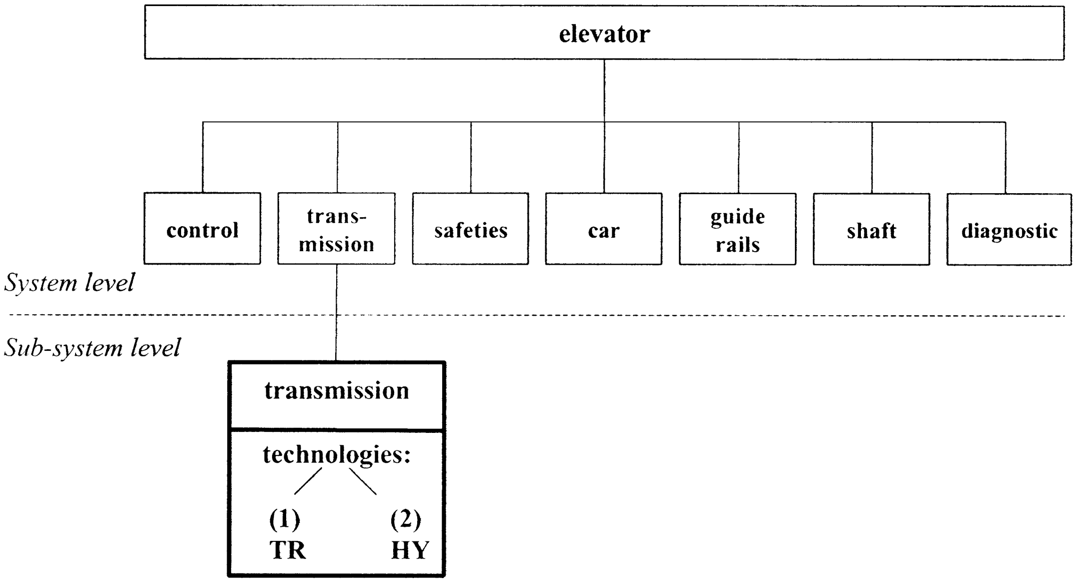

Fig. 1. Elevator and its subsystems.

components and/or standard components. The optional linkage of deflection pulley to the rope guiding indicates this option. We, therefore, analyze neutral components in two ways. In our first analysis, all neutral components are counted as standard components, and in the second analysis, all neutral components are counted as unique components. This assumption changes the unique component composition, hence, allowing us to see the maximum impact of unique components on the modularity of HY and TR elevators.

Since both HY and TR elevators have fundamental and optional linkages as well as three classifications 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 set of values of degree of coupling δ, substitutability factor s, unique component composition b, and the total number of components N in the analysis.

For the sake of illustrating the application of the modularization function at the system level, other subsystems (i.e., control, transmission, safeties, car, guide rails, shaft, and diagnostic) are assumed to have the same degree of coupling value $\delta_{\text{subsystem}}$ as the transmission subsystem. Hence, $\delta_{\text{subsystem}}$ represents the average value of all subsystems. However, a more robust analysis of the modularity would include systematic analysis of these subsystems. A range of modularity levels can exist for the two elevators, with $M_{\text{fundamental}}(u)$ and $M(u)$ representing the basic and maximum modularity relationships, respectively. A comparative analysis of HY and TR elevators is summarized in Table IV.

The graphical interpretation of modularization functions for HY and TR elevators are illustrated in Fig. 3.

Preliminary findings of product architecture modularity of HY and TR elevators include the following.

1) Both elevators are highly modular from the unique component composition perspective, $M_{\text{HY}}(3) = 0.98$ and $M_{\text{TR}}(6) = 0.87$. These relative low values of u indicate that the basic product architectures of HY and TR elevators have components with standardized and well-specified interfaces, where cost saving advantages are gained. Suppliers can be specialized in developing specific capabilities for component development. This explains the decrease in the number of competitors and the emergence of a strong and increasingly important component supplier industry, which is similar to the computer industry (see [15]). This partially explains why market entry barriers for new elevator companies are relatively low.
2) When all linkages are taken into consideration, HY elevators are slightly more modular than TR elevators due to higher substitutability factor ($s = 1.2$), lower unique component composition ($b = 7\%$), and lower degree of coupling ($\delta = 4.59$). Although the three unique components are shared by only two families (low-rise and mid-rise), HY elevators have higher substitutability factor which is attributed by the lower average number of interfaces of NTF components [$k_{\text{NTF}}(avg)_{\text{HY}} = 1.67$ compared with $k_{\text{NTF}}(avg)_{\text{TR}} = 5.00$)]. The degree of coupling of TR elevators ($\delta = 5.01$) indicates that the components are more tightly coupled than HY elevators ($\delta = 4.59$) exhibiting higher synergistic specificity. Graphically, the higher modularity of HY elevators are indicated by the relative slopes of the modularity functions, with $M_{\text{TR}}(u)$ much steeper than $M_{\text{HY}}(u)$. According to market experts at Schindler, HY elevators are considered commodity products with little differentiation potential, since these elevators are classified as low cost products. Generally, the components suppliers of the HY elevator tend to have more power than the suppliers of the TR elevator.
3) When neutral components are classified as unique components, then TR elevators have more leverage in gaining modularity from neutral components. For instance, the transmission of TR elevator has six unique components

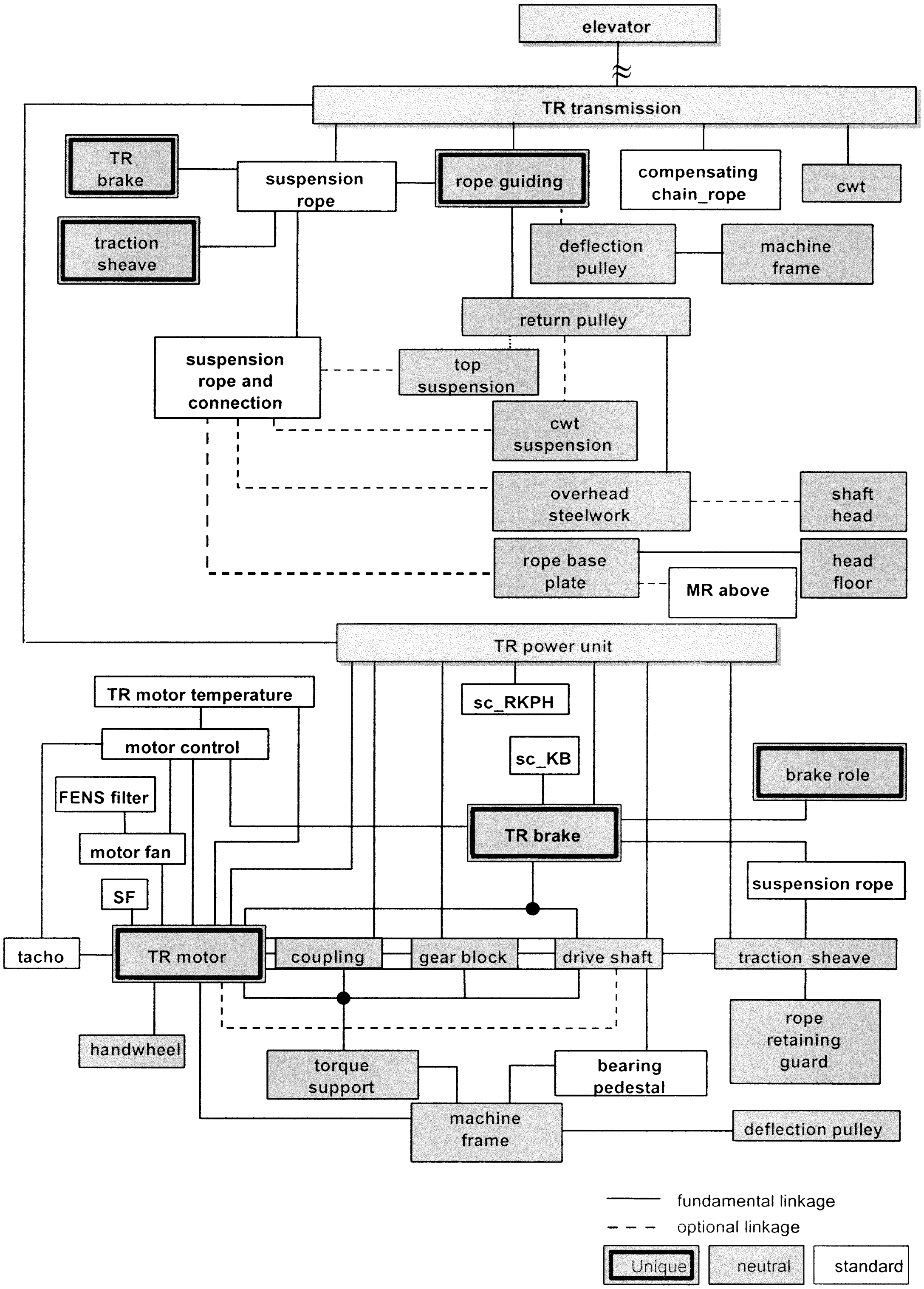

Fig. 2. Partial product architecture of the TR.

and 19 neutral components (that is a total of 25 units). When all the neutral components are treated as unique components, then modularity value of TR elevators, $M_{\mathrm{TR}}(u)$, can range from 0.08 to 0.87, compared with the value of HY elevators, $M_{\mathrm{HY}}(u)$, ranging from 0.47 to 0.98. This suggests that there are more opportunities for TR elevators to become more modular. HY elevators are so modular that even when all the neutral components are treated as unique components, the worst degree of modularity is 0.36 [for $M_{\mathrm{HY-fundamental}}(u)$] compared to a value of 0.07 [for $M_{\mathrm{TR-fundamental}}(u)$]. This means that HY elevators have more leverage with the neutral components in configuring the product architecture for variation and customization than TR elevators. Put it

TABLE IV
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 %
k_{NTF}(avg) = 1.67	k_{NTF}(avg) = 1.67
s = 1.2 components/interface	s = 1.2 components/interface
δ = 4.02 interfaces/component	δ = 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 %
k_{NTF}(avg) = 4.67	k_{NTF}(avg) = 5.00
s = 0.64 components/interface	s = 0.60 components/interface
δ = 4.83 interfaces/component	δ = 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

differently, although HY elevators are more modular, TR elevators have more flexibility from the neutral components.

4) The modularity of both TR and HY elevators can be improved by increasing the substitutability factor [s]. This can be accomplished by incorporating NTF components across more elevator families or by reducing the average number of interfaces of unique components, $k_{\mathrm{NTF}}(avg)$. For instance, suppose that "MR above" (a standard TR component) is replaced by a unique, better performing component (call it MR2). Assuming that the other variables remain constant, we would see a unit increase in u, hence lowering the degree of modularity. However, if MR2 can be used across other elevator families, then the overall degree of modularity is improved. Many innovations in the elevator technology are leading toward component integration rather than decomposition, which also reduce the total number of components and how they are linked. Assume, for instance, that "MR above" is integrated into "rope base plate." The "new rope base plate" needs two interfaces for functionality instead of three, which reduces $k_{\mathrm{NTF}}(avg)$, and the overall degree of coupling δ while increasing the substitutability factor s (if used across other elevator families).

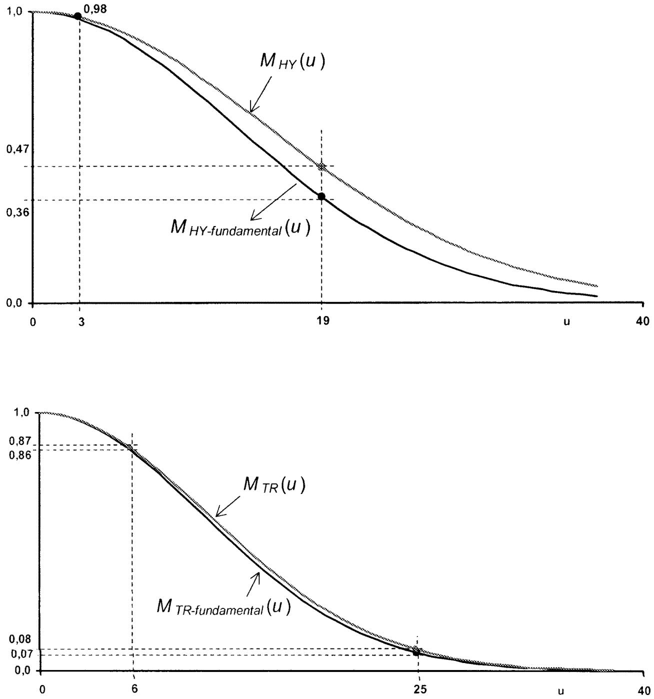

Fig. 3. Modularization functions of HY and TR Elevators.

5) While component modularity is captured by the neutral components, the optional linkages capture interface modularity. When all linkages (fundamental plus optional linkages) are considered, HY elevators have considerably higher leverage for increasing degree of modularity than TR elevators. This is indicated by the larger differences between the modularization functions $M(u)$ and $M_{\text{fundamental}}(u)$, that is, $[M_{\text{HY}}(u) - M_{\text{HY}-\text{fundamental}}(u)] > [M_{\text{TR}}(u) - M_{\text{TR}-\text{fundamental}}(u)]$. The gap can be interpreted as the difference between the most and the least complex configurations possible for TR and HY elevators. It captures the amount of product variety and customization allowed by the product architecture. TR elevators, for instance, have less freedom for creating variations and customization than HY elevators. One explanation may be because the product architecture of TR elevators is more mature than HY elevators'.

The modularization function also allows us to plot the sensitivity graphs for HY and TR elevators, as illustrated in Fig. 4. The sensitivity graphs reveal that TR elevators are more sensitive to increases in the number of unique components, u. This is indicated by the steeper slopes of both HY elevator sensitivity functions, $S_{\text{fundamental}}(M; u)$ and $S(M; u)$, compared with those of TR elevators'.

VI. DISCUSSION AND MANAGERIAL IMPLICATIONS

This analysis shows how degrees of modularization of HY and TR elevators are assessed with the modularization function. Although the analysis we have presented in this paper is limited to transmission technologies, the systematic analysis and application of the modularization function to other subsystems of HY

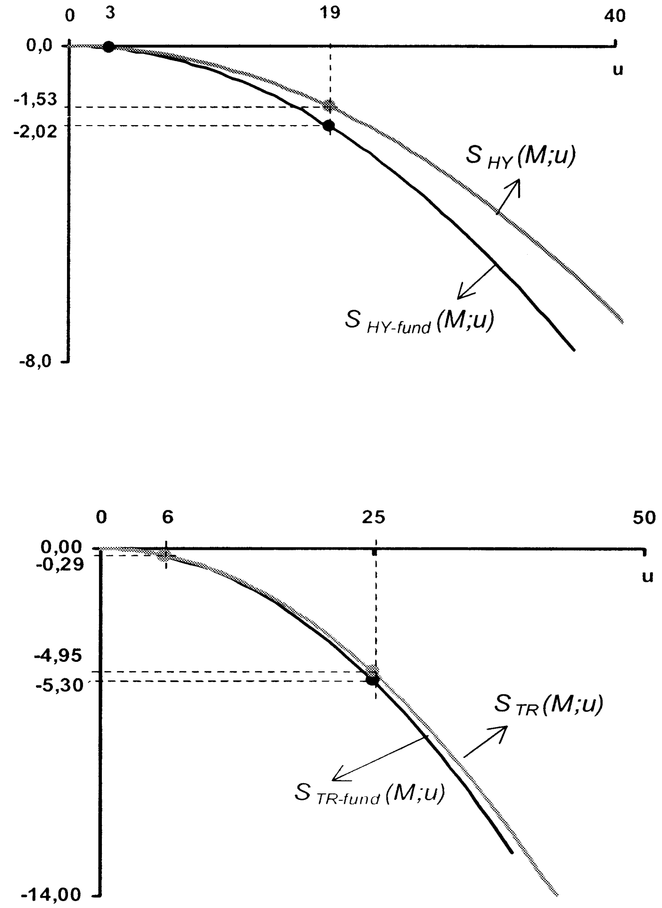

Fig. 4. Sensitivity graphs of HY and TR Elevators.

and TR elevators (i.e., control, safeties, car, guide rails, shaft, and diagnostics) would improve the robustness of the function. The application of modularization function may present management with ideas for strategic planning. For instance, there are signs in the industry indicating that firms are leveraging the TR opportunities for modularization. The market demand for TR elevators is increasing, partly because TR elevators are more ecological efficient and have higher performance than HY elevators, but also because its inherent modular nature allows firms to have more leverage in variation and customization through the selection of components.

According to Schindler experts, leading elevator firms (such as Schindler and Kone) are applying platform thinking to the management of their product architectures.[10] Similarly, Schindler is also strict on cost oriented and variant reduction management of its TR platforms, which takes into consideration how components can leverage the opportunities for modularization. The leading elevator companies are developing new drive technologies, such as linear motors with integrated safety functions. This integration of technologies reduces the number of components and alters the interface relationships with other components, hence changing the overall degree of coupling and substitutability of these new components across elevator families. At the same time, the elevator industry is also incorporating standardized technologies from other industries, such as safety bus (from the automotive industry), printers (from the computer industry), and drives (from the machinery industry). These technologies have standardized interfaces, which means that system compatibility problems (e.g., linking electrical system to the building management system, linking communication system to the security system) are minimized. On the other hand, Schindler is also developing unique, customizable components (i.e., remote monitoring and diagnostics), which greatly influence the firm's after sales and service businesses, and can prevent competitors with low overhead costs from pirating.

Furthermore, in industries characterized by a dominant product design, strict interface management has to be applied in order to benefit from economies of scale and outsourcing potentials. These industries tend to change from proprietary solutions to common standards. Similar trends can be observed in the mobile telecommunication industry, where the global players like Nokia, Ericsson, and Siemens cooperate in order to set standards. Moreover, the classical tradeoff between optimizing manufacturing costs through integrated design versus optimizing life-cycle costs through modular design will shift toward the latter one. One enabler for this trend is the transparency of life cycle costs: the reusability of modules for product variants can lead to significantly lower life cycle costs. Drivers of this trend are economies of scale and scope, maintenance synergies (e.g., the benefits gained from modular components used for preventive maintenance to maximize passenger safety), and improved product quality. The modularization function is one way of capturing the complexities of component innovations into a simple mathematical formula. The model is not a prescription as to how firms should design product architectures, but it raises potential policy and strategic implications of performance, cost, and resource allocation related to product architecture designs.

A. Generalization of the Model

The use of mathematical models involving differential equations, such as the modularization function, is applicable for quantities that change continuously. In addition, functions that take on only discrete values can sometimes be treated as though they have derivatives and satisfy differential equations. The modularization function is best applied at analyzing complex systems such as automobiles, airplanes, mobile phones, computers, etc. In these complex systems, the number of components is enormous, and there are continuous incremental changes to both the process and the system itself, affecting the component composition of a predefined product architecture.

Although we applied the function in only one case study, the fundamental characteristics of the Schindler Elevator case are not unique. Similar tradeoffs between modular and integral product architectures, arising from NTF components, exist for many complex systems in other industries. In order to compete, technology novelties are introduced continuously, often through incremental innovations, such as add-ons and upgrades that are based on present product architectures. Decomposition of the system into more manageable parts is one of the most attractive

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[10] The platform management thinking at Schindler is adopted from the automotive industry, mainly from Volkswagen.

ways to manage the complexity of product designs. The modularization function consolidates the complexities of product architecture variation and customization into a simple formula, allowing managers and researchers to compare, simulate, and predict the implications of technological development on future generations of product architectures.

One interesting extension of the model is to analyze the various tradeoffs imposed by product architecture design strategies (derived from each of the variables) with respect to NPD lead time and costs. For instance, we can take a closer look at the impact of NTF components when their development and manufacturing tasks are outsourced instead of carried out in-house, which would reflect a firm's strategic choices resulting in different lead time and cost alternatives. Many firms are experiencing financial gains from outsourcing, as it holds down the unit costs and investment needed to produce products rapidly, and it frees companies to direct scarce capital where they hold a competitive advantage. Competition among suppliers is likely to exist when a firm buys its components from multiple suppliers. How a firm chooses to decompose its product architectures and how much novelty to introduce to the next generation architectures have a critical role in supplier management policies. For instance, the number of competitors in the elevator industry is decreasing while component suppliers are gaining more bargaining power with the increasing state-of-the-art technology and process complexities embedded in their products.[11] The stronger suppliers are also pushing elevator companies to use standardized components. Modularity management of product architectures should not be conducted in isolation of manufacturing strategy [33], [54] and organizational designs, especially regarding to multiproject management [10]. We are aware that the benefits of economies of substitution depend on the production volume. For instance, it may not make sense for a firm to maximize on economies of substitution when production volume is low. Component integration may be a better strategy than component decomposition. In any case, product architecture designs involve technological development of components, which have to consider how development tasks should be allocated (internally or to suppliers), how they are to be manufactured, and how suppliers are to be managed.

VII. CONCLUSION

In this paper, we have argued that the degree of modularity inherent in product architectures depends on the constituent components and interfaces. Modularity is enhanced when interfaces shared among components in a given product architecture are specified and standardized to allow for greater substitutability of components across product families. We have explained the architectural design decisions—which can range from modular to integral—consider various tradeoffs. In order to capture the complexities of modularization, we proposed the modularization function as a tool to integrate key elements of product architecture modularity into a single measure. The modularization function enabled the systematic analysis of product architectures, that is, we were able repeat the analysis and check for accuracy and interpretation of the empirical data. The application of modularization function was illustrated with product architectures of two dominant elevator systems: traction-pull and hydraulic. The comparative analysis captured the sensitivity and dynamics of these systems created by three types of components (standard, neutral, and unique) and two types of interfaces (fundamental and optional).

APPENDIX
MODULARIZATION FUNCTION FORMULATION

In developing our modularization function, we assume that there is a relationship between the degree of modularization in a given product architecture (e.g., from perfect integral to perfect modular architectures) and the number of NTF components (e.g., $b = 0$ representing no NTF components). For every change in component composition b, or the number of NTF components, we would expect a change in the degree of modularization. The higher the number of NTF components, the lower the degree of modularization. In other words, we want the degree of modularization M to decrease at a rate r that is proportional to the amount of modularization present with each set of NTF components u. If M is the 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 level 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 level of modularization

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

The factor r is a compound factor that takes into consideration the component composition b, degree of coupling δ, and substitutability factor s, and is expressed as the ratio of component composition b to the total degree of coupling δ in a given product architecture, magnified by substitutability factor s

$$r = \frac{b}{s\delta} = \frac{u/N}{s\delta}.$$

As argued, a high aggregate value of δ indicates a product architecture that has a set of components that are tightly coupled, hence, limiting the degree of modularization. The substitutability factor s, on the other hand, enhances product architecture modularity as it measures the sharing of NTF components across product families. We can think of $s\delta$ as the cumulative interface constraint effect of subsystems, across product families. The factor r is simply the rate in which NTF components are averaged out across this total interface constraint effect.

Thus

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

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[11] A Similar trend is observed in the automotive industry. A study by the University of Michigan, Ann Arbor, suggests that as much as 80% of the value added of a car is being generated from the suppliers rather than by the assembler due to the transfer of direct task responsibilities to the suppliers [53].

In differential equation form

$$\frac{dM}{du} = -\frac{u}{Ns\delta}M \quad \text{or} \quad \frac{dM}{M} = -\frac{u}{Ns\delta}.du$$

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

$$M(u) = M_0 e^{-u^2/2Ns\delta}.$$

It is assumed that the amount of modularization is constrained 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

$$M(u) = e^{-u^2/2Ns\delta}.$$

The sensitivity relationship of the modularization funtion $M(u)$ with respect to the number of NTF components u is expressed as follows:

$$S_u^M = \frac{u}{M} \cdot \frac{dM}{du} = -\frac{u^2}{Ns\delta}.$$

The sensitivity function indicates the amount of decrease in modularity $M(u)$ associated with an increase in the number of NTF components u.

REFERENCES

[1] K. R. Baker, M. J. Magazine, and H. L. W. Nuttle, "The effect of commonality on safety stock in a simple inventory model," *Manage. Sci.*, vol. 32, no. 8, pp. 982–988, 1986.

[2] C. Y. Baldwin and K. B. Clark, "Managing in an age of modularity," *Harvard Bus. Rev.*, pp. 84–93, Sept./Oct. 1997.

[3] ——, *Design Rules: The Power of Modularity*. Cambridge, MA: MIT Press, 2000.

[4] R. Boutellier, O. Gassmann, and M. von Zedtwitz, *Managing Global Innovation, Uncovering the Secrets of Future Competitiveness*, 2nd ed. Berlin, Germany: Springer-Verlag, 2000.

[5] C. M. Christensen and R. S. Rosenbloom, "Explaining the attacker's advantage: Technological paradigms, organizational dynamics, and the value network," *Res. Policy*, vol. 24, pp. 233–257, 1995.

[6] K. B. Clark, "The interaction of design hierarchies and market concepts in technological evolution," *Res. Policy*, vol. 14, pp. 235–251, 1985.

[7] K. B. Clark and T. Fujimoto, "The power of product integrity," *Harvard Bus. Rev.*, vol. 68, no. 6, pp. 107–118, 1991.

[8] D. A. Collier, "The measurement and operating benefits of component part commonality," *Dec. Sci.*, vol. 12, no. 1, p. 85, 1981.

[9] ——, "Aggregate safety stock levels and component part commonality," *Manage. Sci.*, vol. 28, no. 11, pp. 1296–1303, 1982.

[10] M. A. Cusumano and K. Nobeoka, *Thinking Beyond Lean*. New York: Free Press, 1998.

[11] ——, "Strategy, structure and performance in product development: Observations from the auto industry," *Res. Policy*, vol. 21, pp. 265–293, 1992.

[12] A. Dogramaci, "Design of common components considering implications of inventory costs and forecasting," *AIIE Trans.*, vol. 11, no. 2, pp. 129–135, 1979.

[13] H. Emmons and A. R. Tedesco, "The modular growth design problem," *AIIE Trans.*, vol. 3, no. 2, pp. 104–114, 1971.

[14] D. H. Evans, "Modular design—A special case in nonlinear programming," *Oper. Res.*, vol. 11, pp. 637–647, 1963.

[15] C. Fine, *Clockspeed*. Cambridge, MA: Perseus, 1998.

[16] C. Fine and D. E. Whitney. (1996) "Is the make-buy decision process a core competence?". [Online]. Available: http://web.mit.edu/ctpid/www/Whitney/morepapers/make_ab.html.

[17] M. Fisher, K. Ramdas, and K. Ulrich, "Component sharing in the management of product variety: A study of automotive braking systems," *Manage. Sci.*, vol. 45, no. 3, pp. 297–315, 1999.

[18] R. Garud and S. Kotha, "Using the brain as a metaphor to model flexible production systems," *Acad. Manage. Rev.*, vol. 19, pp. 671–698, 1994.

[19] R. Garud and A. Kumaraswamy, "Technological and organizational designs for realizing economies of substitution," *Strat. Manage. J.*, vol. 16, pp. 93–109, 1995.

[20] ——, "Changing competitive dynamics in network industries; and exploration of Sun Microsystem's open systems strategy," *Strat. Manage. J.*, vol. 14, pp. 351–369, 1993.

[21] O. Gassmann and M. von Zedtwitz, "Organization of industrial R&D on a global scale," *R&D Manage.*, vol. 28, no. 3, pp. 147–161, 1998.

[22] ——, "New concepts and trends in international R&D organization," *Res. Policy*, vol. 28, pp. 231–250, 1999.

[23] J. H. Gilmore and J. Pine, "The four faces of mass customization," *Harvard Bus. Rev.*, pp. 91–101, Jan./Feb. 1997.

[24] R. M. Henderson and K. B. Clark, "Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms," *Administ. Sci. Quart.*, vol. 35, pp. 9–30, 1990.

[25] J. Hsuan, "Impacts of supplier-buyer relationships on modularization in new product development," *Eur. J. Purchas. Supply Manage.*, vol. 5, pp. 197–209, 1999.

[26] R. N. Langlois and P. L. Robertson, "Networks and innovation in a modular system: Lessons from the microcomputer and stereo component industries," *Res. Policy*, vol. 21, pp. 297–313, 1992.

[27] A. N. Link and G. Tassey, *Strategies for Technology-Based Competition*. Lexington, MA: Lexington Books, 1987.

[28] M. Lundqvist, N. Sundgren, and L. Trygg, "Remodularization of a product line: Adding complexity to project management," *J. Prod. Innov. Manage.*, vol. 13, pp. 311–324, 1996.

[29] M. H. Meyer and A. P. Lehnerd, *The Power of Product Platform: Building Value and Cost Leadership*. New York: Free Press, 1997.

[30] M. H. Meyer and J. M. Utterback, "The product family and the dynamics of core capability," *Sloan Manage. Rev.*, pp. 29–47, Spring 1993.

[31] M. H. Meyer, P. Tertzakian, and J. M. Utterback, "Metrics for managing research and development in the context of the product family," *Manage. Sci.*, vol. 43, no. 1, pp. 88–111, 1997.

[32] J. H. Mikkola, "Modularization assessment of product architectures," DRUID, Working Paper 00-4, 2000.

[33] J. L. Nevins and D. E. Whitney, *Concurrent Design of Products and Processes*. New York: McGraw-Hill, 1989.

[34] J. Orton and K. Weick, "Loosely coupled systems: A re-conceptualization," *Acad. Manage. Rev.*, vol. 15, pp. 203–223, 1990.

[35] U. Passy, "Modular design: An application of structured geometric programming," *Oper. Res.*, vol. 18, no. 3, pp. 441–453, 1970.

[36] J. Pine, *Mass Customization—The New Frontier in Business Competition*. Cambridge, MA: Harvard Bus. School Press, 1993.

[37] D. Robertson and K. Ulrich, "Planning for product platforms," *Sloan Manage. Rev.*, pp. 19–31, Summer 1998.

[38] D. P. Rutenberg and T. L. Shaftel, "Product design: Subassemblies for multiple markets," *Manage. Sci.*, vol. 18, no. 4, pp. B220–B231, 1971.

[39] R. Sanchez, "Strategic product creation: Managing new interactions of technology, markets, and organizations," *Eur. Manage. J.*, vol. 14, no. 2, pp. 121–138, 1996.

[40] ——, "Modular architectures in the marketing process," *J. Market.*, vol. 63, pp. 92–111, Special Issue 1999.

[41] R. Sanchez and J. T. Mahoney, "Modularity, flexibility, and knowledge management in product and organization design," *Strat. Manage. J.*, vol. 17, pp. 63–76, Winter Special Issue 1996.

[42] S. W. Sanderson and M. Uzumeri, *Managing Product Families*. New York: McGraw-Hill, 1997.

[43] M. A. Schilling, "Toward a general modular systems theory and its application to interfirm product modularity," *Acad. Manage. Rev.*, vol. 25, no. 2, pp. 312–334, 2000.

[44] G. Tassey, "Standardization in technology-based markets," *Res. Policy*, vol. 29, pp. 587–602, 2000.

[45] S. Tully, "The modular corporation," *Fortune*, pp. 52–56, Feb. 8, 1993.

[46] K. T. Ulrich, "The role of product architecture in the manufacturing firm," *Res. Policy*, vol. 24, pp. 419–440, 1995.

[47] K. T. Ulrich and D. Ellison, "Holistic customer requirements and the design-select decision," *Manage. Sci.*, vol. 45, no. 5, pp. 641–658, 1999.

[48] K. T. Ulrich and S. D. Eppinger, *Product Design and Development*. New York: McGraw-Hill, 1995.

[49] K. T. Ulrich and S. Pearson, "Assessing the importance of design through product archeology," *Manage. Sci.*, vol. 44, no. 3, pp. 352–369, 1998.

[50] K. Ulrich, D. Sartorius, S. Pearson, and M. Jakiela, "Including the value of time in design-for-manufacturing decision making," *Manage. Sci.*, vol. 39, no. 4, pp. 429–447, 1993.

[51] J. M. Utterback, *Mastering the Dynamics of Innovation: How Companies Can Seize Opportunities in the Face of Technological Change*. Cambridge, MA: Harvard Bus. School Press, 1994.

[52] R. I. van Hoek, B. Vos, and H. R. Commandeur, "Restructuring European supply chains by implementing postponement strategies," *Long Range Plan.*, vol. 32, no. 5, pp. 505–518, 1999.

[53] F. Veloso and S. Fixson, "Make-buy decisions in the auto industry: New perspectives on the role of the supplier as an innovator," *Technol. Forecast. Social Change*, vol. 67, pp. 239–257, 2001.

[54] D. E. Whitney. (1995) "Nippondenso Co. Ltd: A case study of strategic product design". Working Paper CSDL-P 3225. [Online]. Available: http://web.mit.edu/ctpid/www/Whitney/morepapers/nippo-ab.html.

[55] S. H. Wildstrom, "Eureaka! Laptops that share parts," *Bus. Week*, July 14, 1997.

Juliana Hsuan Mikkola (S'86–M'87) received the B.S.E.E. degree from the University of Houston, Houston, TX, the M.B.A. degree from St. Mary's University, San Antonio, TX, the Licentiate degree in science of economics in logistics from the Helsinki School of Economics, Helsinki, Finland, and the Ph.D. degree in operations management from the Copenhagen Business School, Frederiksberg, Denmark.

She was a Design Engineer for seven years with Motorola's Automotive and Industrial Electronics Group, Seguin, TX. Later, she became an Executive Trainee at Motorola's Corporate International Operations Program, Schaumburg, IL, dealing with the management of communications technology in Latin America. She is currently an Assistant Professor of Supply Chain Management with the Copenhagen Business School. Her research interests include modularization in new product development vis-à-vis supply chain management and industry structure, modeling, and portfolio management of R&D projects. Her research has been published in the *European Journal of Purchasing and Supply Management, Technovation* and in a few books.

Oliver Gassmann received the Ph.D. degree in 1996.

In 1996, he joined Schindler Corporation, Ebikon, Switzerland. From 1998 to 2002, he was the Vice President of Technology Management and was responsible for Schindler Corporation's Corporate Research and Technology worldwide. He is currently a Professor of Technology Management and the Director of the Institute of Technology Management, University of St. Gallen, St. Gallen, Switzerland. He has published five books and over 60 publications in the area of technology and innovation management.

Dr. Gassmann is a member of several management and academic boards including the Swiss Board for Science and Research of Economiesuisse, the Comité Stratégique Euresearch, and the Editorial Board of *R&D Management*.