# Modularity and Interface Management:

# The case of Schindler Elevators

*Juliana Hsuan Mikkola*
Copenhagen Business School
Dept. of Industrial Economics and Strategy
*LINK/DRUID*
Howitzvej 60
DK-2000 Frederiksberg
Denmark
Tel:  +45 3815 2941
Fax:  +45 3815 2540
Email: jh.ivs@cbs.dk

## Abstract

Modularity refers to the scheme by which interfaces shared among components in a given product architecture are standardized and specified to allow for greater reusability and commonality sharing of components among product families.  The management of innovation through modular product architecture strategies is gaining increasing importance for firms, not only in practice but also from a theoretical perspective.  It is argued that the degree of modularity inherent in a given product architecture is sensitive and highly dependent upon the number of components and the interface constraints shared among the components, modules, sub-systems, and systems.  This paper applies a mathematical model, termed *modularization function*, for analyzing dynamics and the degree of modularity of a given product architecture by taking into account the following variables: number of components, number of interfaces, new-to-the-firm component composition, and substitutability factor.  The application of the modularization function is illustrated with two elevator systems from Schindler Lifts of Switzerland: traction and hydraulic elevators.  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).

**Keywords:** Modularity, product architecture, interface management, elevator industry

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## 1. Introduction

Globalization, deregulation, more demanding customers, the advances in information and transportation technology contribute to the complexity of designing and managing supply chains (van Hoek et al., 1999) as well as and the management of new product development (NPD) activities (Pine, 1993; Feitzinger and Lee, 1997; Fulkerson, 1997; Gilmore and Pine, 1997; Gooley, 1998). A growing number of high-tech firms (e.g., consumer electronics, automotive electronics) have embraced new approaches to the management of their NPD, manufacturing and supply chain management activities (Gassmann and von Zedtwitz, 1998, 1999; Boutellier et al., 2000). 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, many firms are pursuing modular product architecture strategies.

In assessing modularization at the product architecture level, issues regarding decomposability and integration of components vis-à-vis interface management of these components become an important factor. In a modular design strategy (as opposed to integral design strategy), decomposability of the components and interface compatibility issues must the seriously considered. Consequently, the degree of modularization inherent in a product is sensitive and highly dependent upon the number of components and the interface constraints shared among the components, modules, sub-systems, and systems. Most studies on modularization are 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 sounds reasonable to say that firms should understand the fundamental relationship between components and interfaces at the root of product architecture in order to manage modularity of products. Hence, the two main research questions explored in this paper are: (1) How can we systematically assess the complexities of modularization induced by components and respective interfaces embedded in architectural designs? and, (2) How sensitive is modularity of a given product architecture to changes in its component composition and degree of component substitutability?

In this paper, the concept of *modularity* is examined for assessing the design of product architectures by decomposing a system into sub-systems and modules for analysis. A mathematical model, the modularization function, is applied for analyzing the degree of modularization of two elevator systems from Schindler Lifts, the second largest elevator corporation in the world. The paper is organized as follows. Firstly, a brief literature on modularization, product architecture, and interfaces are reviewed, followed by a brief discussion on the effects of substitutability and components. Secondly, the modularization function is introduced along with the assumptions made for formulating the mathematical model. Finally, the application of the mathematical model is illustrated with two architectures of Schindler Lifts.

### *1.1. Modularity*

Broadly speaking, *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. 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, 1994; Garud and Kumaraswamy, 1995)[1].

A great body of literature on modularization focuses at the role of modularization vis-à-vis end users, specifically with respect mixing-and-matching of components (Sanchez, 1999; Schilling, 2000; Garud and Kumaraswamy, 1995; Sanchez and Mahoney, 1996; Pine, 1993) for creating product variety, and product architecture choices (Ulrich and Eppinger, 1995; Meyer et al., 1997; Robertson and Ulrich, 1998; Meyer and Lehnerd, 1997; Mikkola, 2000a, 2000b). Although mixing-and-matching of components is one of the advantages enabled by modularization, its complexities are also dependent on the degree of standardization and customization of the components vis-à-vis respective linkages embedded in product architectures. Mixing-and-matching of components tends to be more visible with products tailored to the consumers (e.g., Swatch watches, Sony Walkman, accessories for mobile phones, etc.), at later stages of value chain. Whereas modular innovation (Christensen and Rosenbloom, 1995; Henderson and Clark, 1990; Hsuan, 1999a) in the form of unique components inserted in product architectures for differentiating a product from that of the competitors' is virtually invisible to the eyes of consumers, and tend to be more critical at the early stages of the value chain (e.g., anti-lock brake systems, air bags,

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[1] Terms used to describe modularization includes *modular innovation* (Christensen and Rosenbloom, 1995; Henderson and Clark, 1990; Hsuan, 1999a), *modular system* (Baldwin and Clark, 1997; Langlois and Robertson, 1992, Boutellier et al., 1999), *modular components* and *modular product design* (Schaefer, 1999; Sanchez and Mahoney, 1996; Mikkola, 2000a, 2000b), *modular product architecture* (Sanchez and Mahoney, 1996; Lundqvist et al., 1996; Ulrich and Eppinger, 1995), and *remodularization* (Lundqvist et al., 1996). A list of their definitions can be found in Hsuan (1999a).

synthetic ropes for elevators, etc.). In this paper modularity is defined as the scheme by which interfaces shared among components in a given product architecture are specified and standardized (Sanchez and Mahoney, 1996) to allow for greater reusability and commonality sharing of components among product families.

### *1.2. 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 what their interfaces are with the rest of the device (Ulrich, 1995; Ulrich and Eppinger, 1995). Product architecture is often established during the product development process. This takes place during the system-level design phase of the process after the basic technological working principles have been established, but before the design of component and subsystems has begun.

Product architectures can vary from modular to integral. Modular product architectures are used as flexible platforms for leveraging a large number of product variations (Gilmore and Pine, 1997; Meyer et al., 1997; Robertson and Ulrich, 1998; Sanchez, 1996; Sanchez 1999), enabling a firm to gain cost savings through economies of scale from component commonality, inventory, logistics, as well as to introduce technologically improved products more rapidly. Some of the reasons for product change include upgrade, add-ons, adaptation, wear, consumption, flexibility in use, and reuse (Ulrich and Eppinger, 1995). Modular architectures enable firms to minimize the physical changes required to achieve a functional change. Changes to product variants often are achieved through modular product architectures where changes in one component do not lead to changes in other components.

Conversely, in integral product architectures, one-to-one mapping between functional elements and physical components of a product is non-existent, and interfaces shared between the components are coupled (Ulrich, 1995). Changes to one component cannot be made without making changes to other components. With integral product architectures, firms may be able to customize their products to satisfying each customer’s particular needs. Costs of customized components 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.

### *1.3. Interfaces*

Interfaces are linkages shared among components, modules, sub-systems of a given product architecture. Interface specifications define the protocol for the fundamental interactions across all components and interfaces comprising a technological system. The crystallization and development of interface specifications has a tremendous impact on setting worldwide industry standards (e.g., GSM, TDMA, and AMP telecommunication standards). Typical interface specifications for a consumer electronics product at the NPD level, for instance, often includes the tolerance specification of the components with respect to manufacturing processes, operating frequency bandwidths, maximum heat dissipation threshold, voltage and current requirements, housing dimensions, to name a few. Sanchez (1999) furthermore classify seven different types of interfaces[2]: attachment, spatial, transfer, control and communication, environmental, ambient, and user interfaces.

For the purpose of mathematical modeling, all interfaces are treated as physical linkages. Moreover, interface constraints are restrictions imposed by the components and how interfaces are shared amongst these components in a given product architecture. When a given product architecture is decomposed into sub-circuits, the interface constraints of these sub-circuits can be evaluated in stages. For example, the so-called components of ‘closed assembled systems’[3] can often be divided into two groups: electronic (e.g., resistors, capacitors, semiconductors) and mechanical (e.g., pins, nuts, bolts, housing). Interface management also deals with the issues of component integration or multiplexing, as opposed to decomposition or de-integration of a system into smaller components [4].

### *1.4. Components and Substitutability*

Standard components are often off-the-shelf parts, and have well defined technical specifications that are generally accepted as industry standards. These parts are often listed in catalogues with low unit prices varying accordingly with the volume

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[2] For interfaces relevant in software platform designs see Meyer and Lehnerd (1997).

[3] A ‘closed assemble system’ is a system that is enclosed by sub-systems with clear boundaries, and the individual sub-system must be linked together via interface and linkage technologies (Tushman and Rosenkopf, 1992). Examples are cars, computers, and mobile phones.

[4] For a discussion of the effect of integration/multiplexing of components in a system and its impact on modularization vis-à-vis degree of supplier-buyer interdependence, see Hsuan (1999b).

purchased. New-to-the-firm (NTF) components, on the other hand, are components that are usually considered as unique by a firm, as such components often have high technological risks by inducing changes at interfaces shared with other components, thus altering the configuration of a product architecture. Unique components cannot be sourced from the component suppliers, therefore have to be developed. Often the risks are well justified by the technical superiority of these components, significantly improving the overall performance of the product. The use of NTF components is strategic in nature because the integration of NTF components into a product architecture are often hard to be imitated by competitors (i.e., modular innovation), thus creating competitive advantages for the firm, at least in the short-run. But too many NTF components hamper innovation due to the increasing complexity in interface compatibility issues with other components in the product.

Product architecture defines the way in which components[5] interact with each other. The substitutability factor of product architecture is a function of the number of product families made possible by the modular component as well as the number of interfaces required for functionality. For example, if a component of a given product architecture can be used in 10 families (or 10 times the same component), and 2 interfaces must be shared with other components/modules/sub-systems for functionality, then the substitutability factor of the product architecture is 5 components per interface. A perfect modular product architecture is comprised of standard components with high substitutability, allowing for high reusability and high commonality sharing of components. Conversely, a perfect integral product architecture is comprised of NTF components with low substitutability, allowing for

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[5] Depending on the level of analysis, a component can be a part, a module, a sub-system, or a system.

low reusability and low commonality sharing of components. Here it is assumed that the degree of modularization in a given product architecture is constraint by the composition of its components (number of standard and NTF components), interfaces shared among the components, and degree of substitutability. Hence, substitutability factor has implications for: (1) reusability and commonality sharing of next generation platform designs, and (2) the potential for a high substitutability factor is obtained when components are designed with reusability and commonality sharing in mind.

A higher level of modularity can be achieved through:

- physical reduction of number of interfaces through the integration of components
- standardization of interfaces
- multi-functionality of the sub-modules (substitutability)

## 2. Research Methodology

The research project was initiated at Schindler 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.

## 3. The Modularization Function

The modularization function was first derived to analyze degree of modularization in a given product architecture of automobile systems. Although automobiles and elevators are different systems, the complexity of modularity imposed by components and respective interfaces are similar[6] and can be translated into mathematical forms, hence making it possible for the systematic analysis of product architectures of dissimilar systems to take place. The beauty 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. Although mathematical models are powerful for analyzing dynamic behavior of the variables, it is confined to the limited number of variables and the can become quite complex with increasing number of variables.

The amount of modularization in a given product architecture is a function of the composition of NTF components, substitutability factor, and interface constraints.

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[6] Both automobiles and elevators are comprised of electrical, mechanical, and electro-mechanical devices where interfaces linking various technologies can be clearly identified.

Interface constraints ($d$) 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 we simply approximate it as the ratio of the total number of interfaces ($k_c$) per the number of components ($n_c$) in a sub-system of a given product architecture:

$$d \approx \frac{\sum k_c}{n_c}$$

The modularization function, $M(u)$, is shown in Equation 1. It 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) [7].

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

$M(u)$ - Modularization function

$S_u^M$ - Sensitivity function

$u$ - number of NTF components

$N$ - total number of components

$s$ - substitutability factor

$d$ - interface constraint factor

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[7] Refer to Mikkola (2000a, 2000b) for the formulation and derivation of the function, and the application of the modularization function with two product architectures of Chrysler Jeeps windshield wipers controllers.

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

$$S_u^M = \frac{u}{M} \cdot \frac{dM}{du} = -\frac{u^2}{Nsd} \qquad \text{Equation 2}$$

The unit of analysis is a black box of which the functional specification is set by the buyer and the detailed engineering (including design, purchasing, and manufacturing activities) is the responsibility of the supplier. The following assumptions are made in deriving the model:

1. NPD of a black box[8] is used, implying that the product's functional specifications, 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 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 modularity.

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

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

competitors. Thus, it is assumed that there should be some amount of NTF components in a given product architecture.

5. All standard components are equally critical.
6. All NTF components are equally critical.
7. All interfaces (i.e. electrical, logical, physical) are equally critical.

The assessment of degree of modularization in a given product architecture involves 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 (BOM).
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.

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

## 4. Role of Modularity in the Elevator Industry

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. Modularity and standardized interfaces 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. In our analysis we concentrate on the traditional elevator architecture which still accounts 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).

### ***4.1. Description of the Elevator System***

Based on UML (Unified Modeling Language) model, several hundreds of components with respective interfaces are documented for every traction and hydraulic elevator at Schindler. The UML model allows a comfortable analysis and interpretation of the product architecture on different aggregation levels. Figure 1 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.

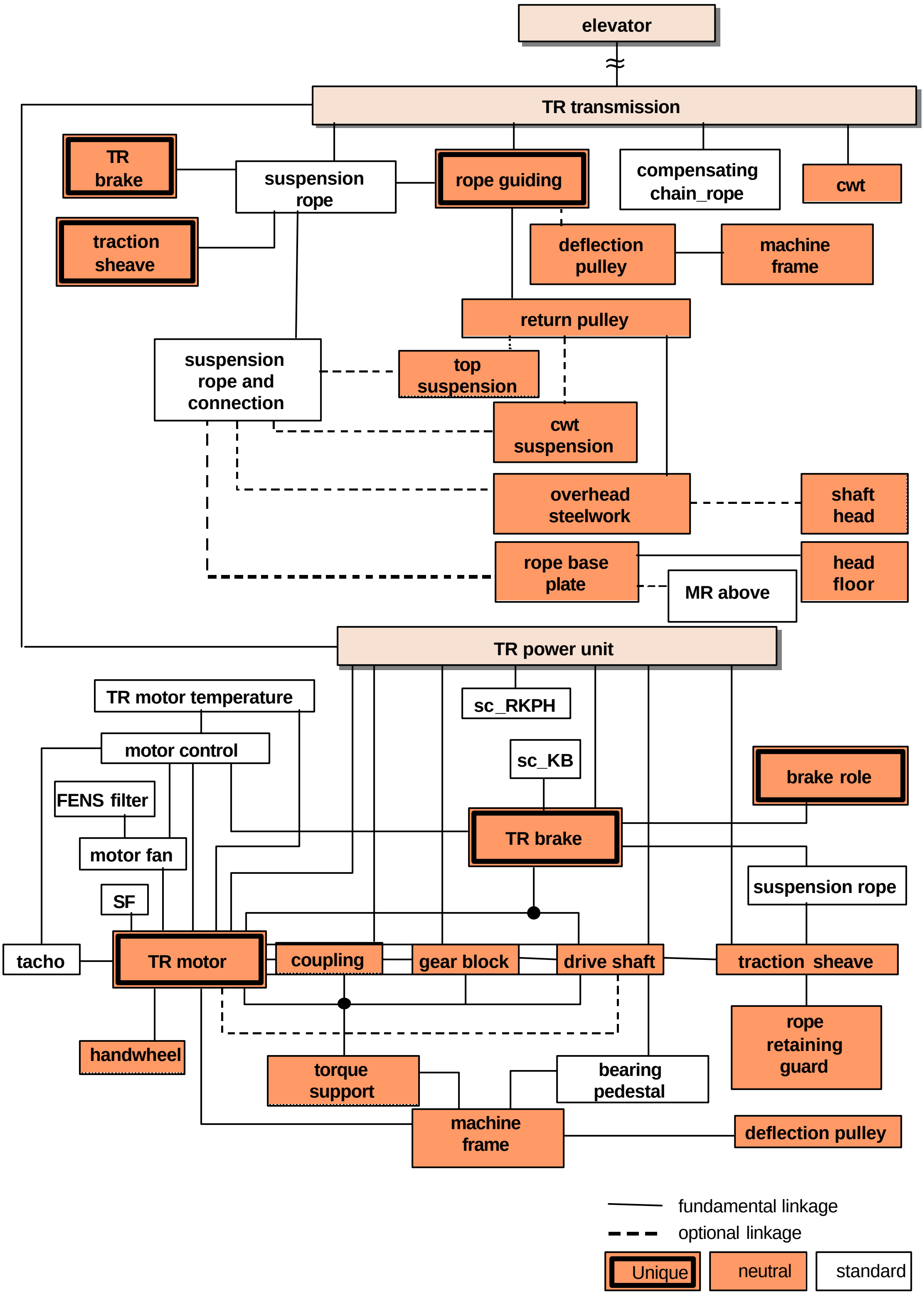

**Figure 1. Partial product architecture of traction elevators (TR).**

In order to illustrate how the modularization function can be applied we selected the transmission sub-systems of both HY and TR elevators for a 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 2.

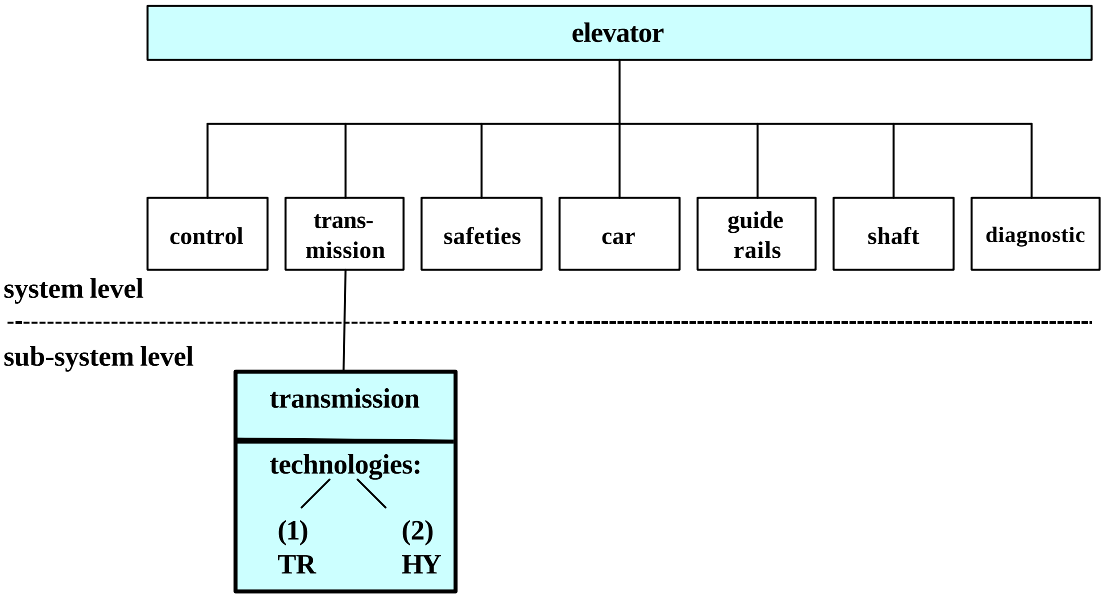

**Figure 2. The elevator and its sub-systems.**

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 number of unique 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. Comparative Analysis of Traction and Hydraulic Elevators in terms of Modularity*

For both Traction Elevator (TR) and Hydraulic Elevator (HY), the analysis starts at the sub-system level with their respective partial product architectures such as the one shown in Figure 1. 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 set of interface constraint value $d$, substitutability factor $s$, unique component composition $b$, and the total number of components in the analysis $N$. Hence a range of modularity levels can exist for the two elevators, with $M_{fundamental}(u)$ and $M(u)$ representing the basic and maximum modularity relationship 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 3 and Figure 4, respectively.

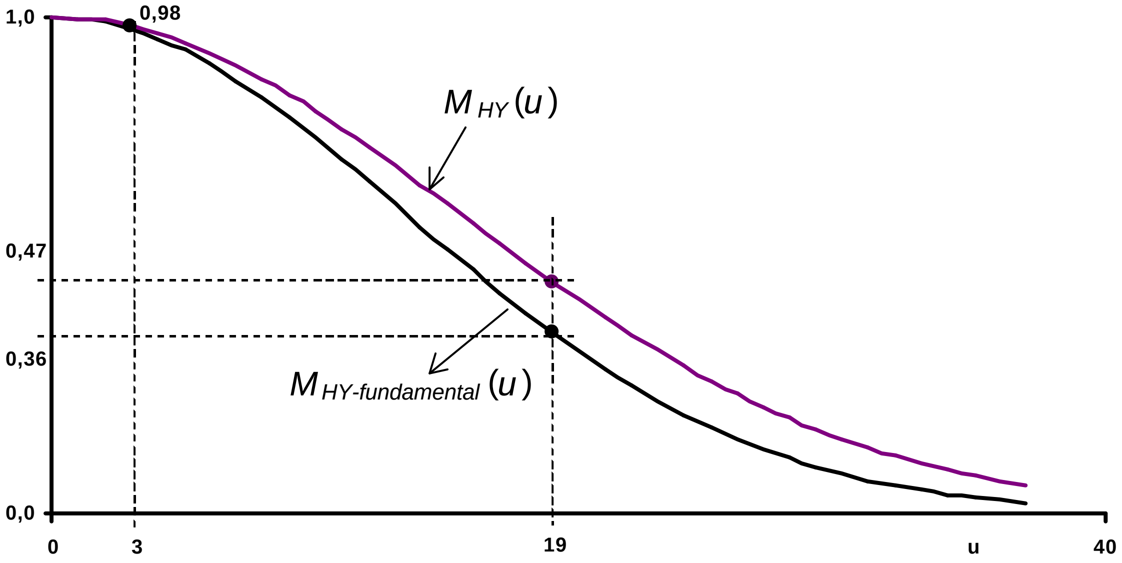

**Figure 3. Modularization function of HY elevators.**

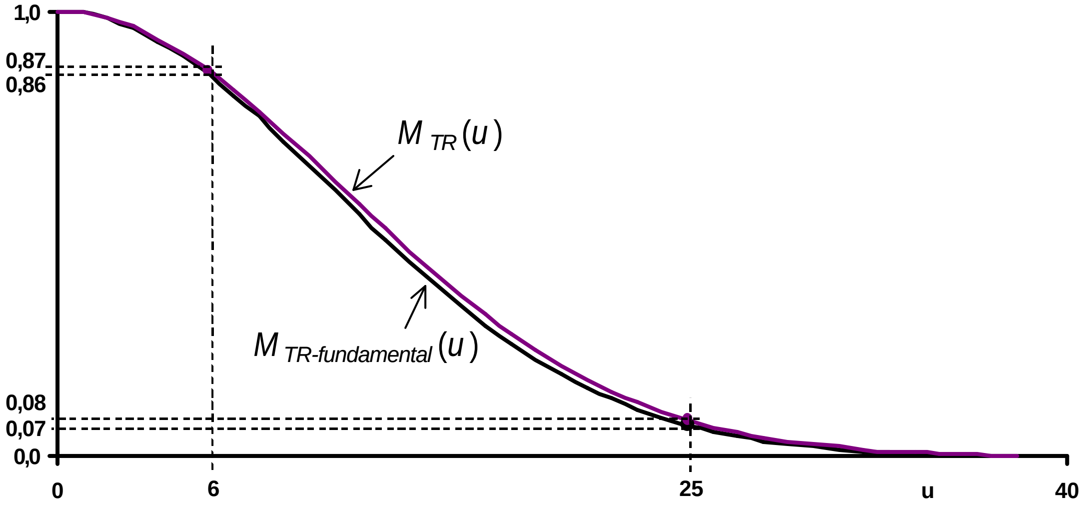

**Figure 4. Modularization function of TR elevators.**

Some preliminary findings of HY and TR elevators with modularization function 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.

The modularization function also allows us to plot the sensitivity graphs for TR and HY elevators, as illustrated in Figure 5 and Figure 6. The sensitivity graphs reveal that TR elevators are more sensitive to increases in the number of unique components than HY elevators, $u$. This is indicated by the steeper slopes of both HY elevator sensitivity functions, $S_{fundamental}(M;u)$ and $S(M;u)$, compared with those of TR elevators.

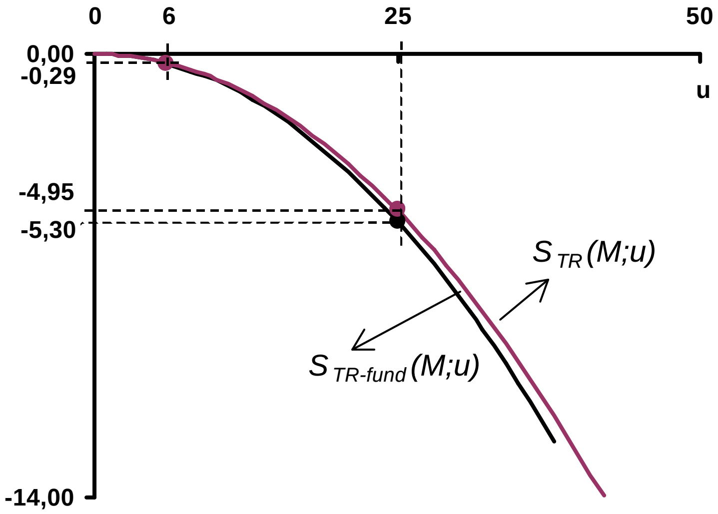

**Figure 5. Sensitivity graph of TR elevators.**

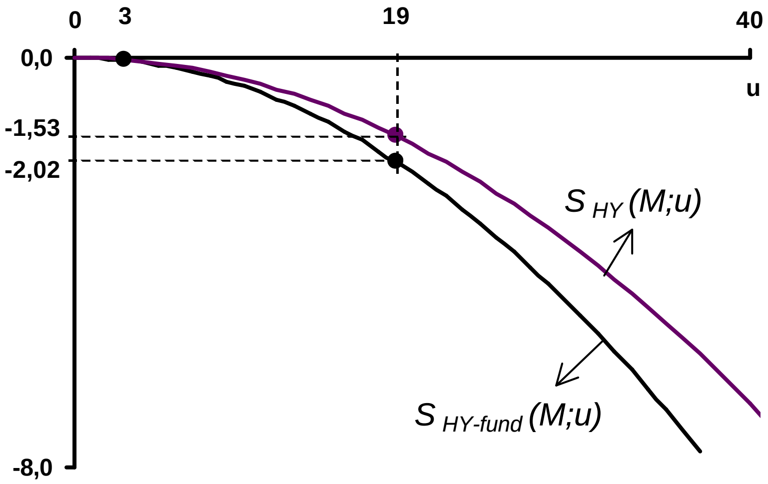

**Figure 6. Sensitivity graph of HY elevators.**

## 5. Summary and Outlook

This paper analyzed modularity vis-à-vis interface management of components in a given product architecture. It was argued that in order to gain a better understanding of the modularity dynamics, we should have a systemic approach to assessing the relationships shared between components and respective interfaces in a given product architecture. A mathematical model, termed modularization function, was applied for analyzing modularity by taking into account the following variables: number of components, number of interfaces, unique component composition, and substitutability factor. The application of the model was illustrated with two dominant elevator systems from Schindler Lifts for comparative analysis: traction elevator and hydraulic elevator.

### *5.1. Managerial implications*

Newest technology developments in the elevator industry will have a big impact on the product architecture and the degree of modularization. The leading elevator companies are developing new drive technologies, such as linear motors with integrated safety functions. This results in dramatically reduced number of components and interfaces. At the same time the substitutability and interface constraint factor will increase.

In industries with dominant design character, a strict interface management has to be applied in order to benefit from economies of scale and outsourcing potentials. These industries are changing from proprietary solutions to common standards. Similar trends can be observed in the mobile communication industry, where the global players like Nokia, Ericsson and Siemens cooperate in order to set standards.

The classical trade off between optimizing manufacturing costs through integrated design and optimizing life cycle costs through modular design will shift towards the latter 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 are economies of scale and scope, maintenance synergies and improved product quality. The importance of modularity will further increase.

### *5.2. Limitations of the mathematical model*

The use of mathematical models involving differential equations, such as the one introduced in this paper, is applicable for quantities that change continuously, and sometimes with functions that take on only discrete values can be treated as though they actually have derivatives and satisfy differential equations. Consequently, the mathematical model presented in this paper is only applicable for analyzing large complex systems (such as automobiles, elevators, ships, rockets, telecommunications systems, etc.) in which the number of components is enormous involving continuous incremental changes to both the process and system itself affecting the component composition of a pre-defined product architecture (either at the production line or at with the development engineering at improving its performance).

The robustness of the model is increased as we incorporate more sub-systems into the analysis of the elevator. So far, the analysis done in this paper merely provides an introduction as how the dynamics of elevator system in terms of modularity at the product architecture level can be analyzed. The model can also be extended to include other variables, however this may make the mathematical function extremely complex.

### *5.3. Future research*

As this paper only reflects preliminary findings of the modularity and interface management of traction and hydraulic elevators, the validation of the mathematical model has to be extended to other industries. We expect similar results in other industries with modular systems such as automotive, aircraft/aerospace, and computer industry.

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, and cost/benefit analysis of modularity.

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