On the Link between Modularity and Cost – A Methodology to assess Cost Implications of Product Architecture Differences

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***Abstract* - Modularity has received renewed interest as a product design strategy to accommodate the competing goals of low cost and high levels of variety and flexibility. Modularity has been associated with numerous advantages for firms and customers, including faster product development, greater product variety, and allowing customers to customize products. However, there is a lack of clear understanding of the cost implications of modularity. One reason for this gap is the use of the term 'modularity' for similar, yet often slightly different, phenomena in different contexts, disciplines, and industries. Consequently, modularity is very difficult to operationalize. This paper presents a methodology to address this problem. Arguing that modularity is actually a bundle of product characteristics rather than a single dimension, the method proceeds in three steps. First, unbundling modularity into multiple dimensions of the product architecture allows one to comparatively measure the differences among products along the individual dimensions. Second, building on process-based cost modeling tools, a cost estimation procedure calculates the product costs for the selected life cycle or supply chain phases. The third step links the cost differences to individual product architecture differences. These links can improve the understanding of how individual dimensions of the product architecture affect different costs along the supply chain. A case study of automotive doors is used to demonstrate the methodology.**

I. INTRODUCTION

Increasing market fragmentation and decreasing product life cycles often make it difficult to recoup investments through classic mass production. Modularity has been suggested as a product design strategy to accommodate the competing goals of low cost and high levels of variety and flexibility. However, modularity has been usually described either in high-level generic terms or very product specific. This lack of agreement on definitions has made it also difficult to understand the cost implications of modularity. In this paper, we present a methodology to address this problem. We argue that modularity is actually a bundle of product characteristics rather than a single dimension. Consequently, we propose a multi-dimensional product architecture mapping to distinguish products along the individual dimensions, a separate cost evaluation process, and a linking step. The methodology identifies links with much finer granularity than the aggregated construct 'modularity' and improves the understanding of how individual dimensions of the product architecture affect the different costs along the supply chain. The remainder of the paper is organized as follows. The next section discusses the theoretical and conceptual underpinnings of the methodology. Section 3 introduces two product designs as examples. Section 4 uses these examples to apply the method in all three steps. Section 5 concludes with a discussion of how the method can link business goals to design advice.

II. CONSTRUCTING THE LINK BETWEEN MODULARITY AND COST

A. Separation of design description and evaluation

One source of the ambiguity that accompanies claims of modularity's advantages is the perspective-specific nature of many claims. Modularity has been found to be advantageous for product development performance [3, 10], for accustoming user needs across product families [14], or for minimizing the product's environmental end-of-life impact [6]. Each of this approaches focuses on a different performance dimension. As a result, the different analyses arrive at different module definitions, i.e., they define modularity differently.

Given this lack of agreement about the definition of modularity beyond high-level concepts, there appears to be a need for separating product descriptions from their evaluations. In order to better understand the effects of multiple design choices on the perspectives involved in designing, making, using, and retiring a product, it is necessary to be able to distinguish one product architecture from another, independent of any particular performance measurement. We propose to look at cause and consequence independently, and to consider three factors: (1) what constitutes modularity, (2) what costs are considered, and (3) how to construct the link between (1) and (2).

B. What is Modularity?

Modularity has been described in terms that are either very general or very product specific. General terms, such as 'interchangeable components' or 'mix-and-match capability,' are broadly applicable but very difficult to operationalize. In contrast, the product-specific modularity descriptions are difficult to apply across industry boundaries. Some researchers understand modules as perfectly interchangeable parts, others focus on product configuration problems, while others concentrate on interface characteristics to specify modularity. Our analysis has shown that modularity is not a single feature but rather a bundle of product characteristics [4]. Which of these characteristics are emphasized usually depends on the product life cycle stage of interest. Consequently, the term modularity alone is of limited use and we propose the product architecture as an alternative to describe and compare products.

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C. *Product Architecture to replace Modularity*

Ulrich has described the product architecture as "the scheme by which the function of a product is allocated to its physical components." He distinguishes two archetypes of product architectures: "A modular architecture includes a one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components. An integral architecture includes a complex (non one-to-one) mapping from functional elements to physical components and/or coupled interfaces between components." [11], p.422.

While conceptually powerful, this notion is difficult to operationalize. Since these extreme archetypes almost never exist in reality, it is necessary to locate different real product architectures relative to these extremes, or at least, relative to each other. Therefore, we extend Ulrich's product architecture definition on three levels. First, we argue that the function-component allocation and interface characteristics are product features that can vary independently from each other. Second, both dimensions *allocation* and *interfaces* are themselves multi-dimensional constructs. Third, since the notions of *modular* and *integral* are associated with an allocation of the functionality to the product, an aggregation for the entire product appears to create unnecessarily imprecise results. It is possible for a product to exhibit modular characteristics in some portions and more integral ones in others.

Consequently, the descriptive product architecture framework developed in this research 'unbundles' modularity by replacing it with a multidimensional product architecture construct, which can measure differences along all dimensions individually. The methodology is presented in detail and illustrated with an example below.

D. *What Costs are considered?*

Every product runs through multiple phases in its life. For an individual product these are: development, production, use, and retirement. For most of today's mass produced consumer products, the production stage is where a significant fraction of the life cycle costs occur. The example of the methodology below focuses on the production stage, but could include any of the other phases.

For cost estimations of the production stage particularly suitable are process-based technical cost models. Technical cost models incorporate first principle engineering knowledge (e.g., kinetics and thermodynamics of the process) on how product and process choices impact process requirements, cycle time and yield, and ultimately unit costs [5].

Technical cost models are also well suited for the analysis of the cost impacts of product architecture differences because they permit controlling for alternative factors influencing costs. In the example below, manufacturing processes are modeled using technical cost models, logistics costs apply analogue spreadsheet calculations, and variety related costs are simulated.

E. *How to link Product Architecture and Cost*

Once comparative product architecture analyses and cost models are constructed separately, their interaction can be explored. Ultimately, this allows one to link business strategies and their economic consequences to design advice.

III. TWO DIFFERENT PRODUCT ARCHITECTURES

To present the methodology and its application, two car door structures are introduced as product examples. We assume that the two products deliver identical functionality, but represent different product architectures. Based on real data, both designs are modified in minor dimensions to ensure comparability. Product design and manufacturing processes of both products are described below. For brevity, the final trim process is not included.

A. *Door Design A: Conventional Door*

The first door design represents the vast majority of car doors that are built today. Hence, it is referred to as the *conventional door.* This door structure consists of a shell shaped construction that is formed by two large stamped steel panels: the door inner panel and the door outer panel. In addition, several smaller steel stampings are used as reinforcements, in particular for the hinge area, the latch area, and the belt area. An anti-intrusion beam made from high-strength steel provides side impact protection (Fig. 1).

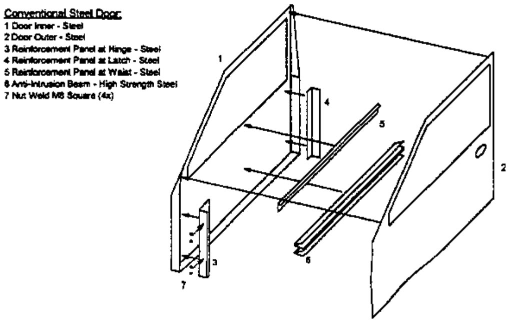

Fig. 1: Door Design A

With the exception of the anti-intrusion beam, all panels and reinforcements are manufactured from steel sheet, employing stamping as material forming process. The anti-intrusion beam is manufactured by using a hot roll-forming process. During subassembly, the smaller stampings and the anti-intrusion beam are welded to the door inner panel before the inner and the outer panels are joined using a flange hemming process, in addition to some spot welds to fix the two panels in their relative positions.

This welded door structure, the door-in-white, is then attached to the body-in-white, which next travels to the paint shop, where car body and closures are painted jointly. After painting, the doors are removed from the body and sent to the final assembly line.

B. *Door Design B: Extrusion Frame Door*

The second door architecture is characterized by its structural part: a frame welded from aluminum extrusions. For this reason this design is henceforth referred to as

Extrusion Frame Door. The structural component of the extrusion frame door is a frame that is formed by several aluminum extrusions (Fig. 2). A U-shaped extrusion forms the lower frame (1). Two straight extrusions serve as belt reinforcements inner (3) and outer (4). A diagonal reinforcement solves for statically determinacy and provides the function of an anti-intrusion beam (5). Additional reinforcements increase the stability of the latch area (8+9). Extra brackets provide mounting surfaces for the mirror (11) and the hinges (12+13).

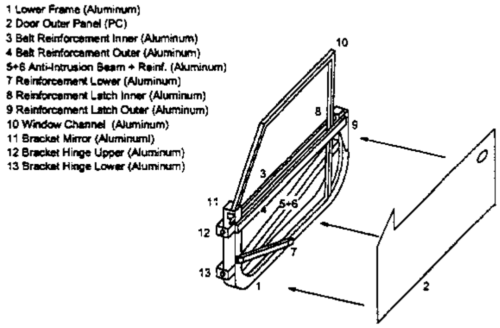

Fig. 2: Door Design B

Most of the frame's parts are extrusions; some reinforcements are stamped (e.g. the reinforcements in the latch area). Several of the extrusions require subsequent bending. Regarding their geometry, the stampings are product specific (in particular the bracket for the hinges). The subassembly process step is represented by the assembly of all but two extrusions using a welding process. The two-part window channel (10) is assumed to be assembled by welding in a separate operation. The window channel is subsequently mechanically fastened to the rest of the frame during subassembly. The outer panel is an injection molded thermoplastic material (compare [9]).[1] For this door design, the door outer panel is the only door component that is painted. After being painted separately, it is delivered directly to the final assembly line where it is attached to the frame with snap-fit connections.

IV. METHODOLOGY

A. *Comparative Product Architecture Analysis*

The framework to compare product architectures follows a systems idea by proposing that every product description consists of two major dimensions: its elements and the relations between them. We will call the elements *components* and the relations *interfaces*.[2]

1. *The Elements: Function-Component Allocation Scheme*

To build on the definition that a characteristic feature of a product architecture is the way in which functions are allocated to components, requires a mechanism to determine and measure this dimension reliably. We have developed rules that govern the selection of functions and components as well as the allocation process.

Both functions and components for assembled products exhibit hierarchies. For the product architecture analysis, functions are selected on rather high levels to avoid pre-specification of technical solutions. Next, components are selected on a *corresponding* level. In other words, the choice of the physical architecture level should reflect the choice of the level of the functional hierarchy. Finally, the allocation process can use binary or weighted factors. Binary assessments reflect a component's participation in a function in a yes/no fashion, percentages describe the contribution relative to other components.

This function allocation using matrices allows the computation of two indices for each function. First, the number of components involved in delivering the functions, and second, the total number of functions this set of components contributes to. These two indices create a space in which each function's position can be determined, relative to the ideal one-to-one notion of 'perfectly modular.' The pattern of all functions together reflects the product as a whole.

Mapping all four functions for the conventional door reveals that different functions are located in different regions of the FCA-map (Fig. 3). The function *structure*, for example, is found in the integral-complex region because almost all components of the design contribute to this function. In contrast, the function *aesthetic appearance* is in the modular-like region because it is solely provided by one component: the door outer panel. It sits not at the corner of the map, i.e., the spot of perfectly modular functions, because the outer panel also contributes significantly to the function *structure*. The two remaining functions, *side impact protection* and *carry other parts*, are located in the integral-consolidated region because they are predominantly provided by a few (one or two) components that simultaneously also provide other functions.

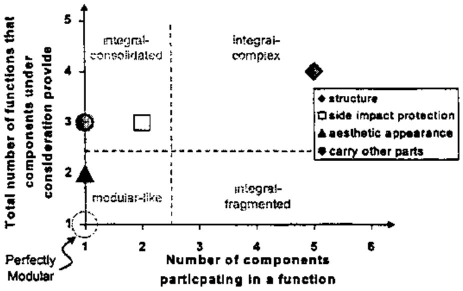

Fig. 3: Function-component allocation (FCA) scheme for conventional door

Compared to the conventional door, the extrusion frame architecture exhibits a smaller number of components - on the hierarchy level under consideration (Fig. 4). Thus, the functions of this architecture are, on average, located closer to the left of the function-component map, i.e., in the integral-consolidated region. There is, however, another significant difference between this architecture and the previous one. The extrusion frame architecture shows perfect function separation of one function from the rest – and the remaining functions are consolidated in one component. While the function

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[1] Alternatively, outer panel have been manufactured from thermoset materials too ([1]).

[2] The term *component* serves here as a pure placeholder. It includes everything above simple connectors, i.e. subsystems, modules, components, or parts.

aesthetic appearance is completely – and exclusively – provided by the components 'door outer panel' and 'window frame,' the functions *structure*, *side impact protection*, and *carry other parts* are completely – and exclusively – provided by the 'frame.'

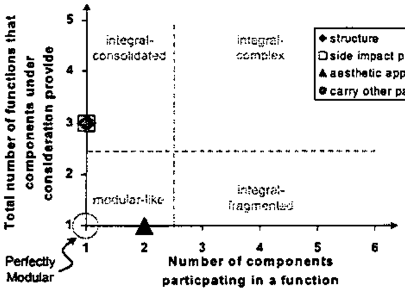

Fig. 4: Function-component allocation (FCA) scheme for extrusion frame door

2. *The Relations: Interface characteristics*

Interfaces' conditions are often described with terms like 'coupling' or 'dependence.' To make the dimension *interface* measurable, we group the information into three categories: the interfaces' role for the product function ('intensity'), their role for making, changing, and unmaking of the product ('reversibility'), and their role with regard to substitutes ('standardization'). Each interface characteristic is measured on the function level.

Intensity. Components can interact in multiple ways during the product's operation. Building on Pimmler and Eppinger [7], we distinguish these interactions by their nature and intensity. Interfaces can be spatial, or they can transmit material, energy, or signals, or any combination of the above. Intensity is measured on a five-point scale between desirable (+2) and detrimental (-2). A matrix containing all components in both first row and first column is used to document the assessment. For comparative purposes, the results can be aggregated on a per-function level. The aggregated results are displayed on the vertical axes of the product architecture maps.

Since the example focuses on the structures of the door designs, almost all interfaces in both designs are spatial in nature. Most spatial interfaces also transmit mechanical forces beyond those to keep the component attached. For this reason, both designs receive a high level assessment with respect to intensity for most of their interfaces. An exception is the function *aesthetics* at the extrusion frame door. The component predominantly providing this feature is the door outer panel, and its interface with the rest of the product only has to hold the panel itself in place. Consequently, the rating for it is slightly lower, compared to the other interfaces of the two example designs. The circles on the vertical axes in Fig. 5 and Fig. 6 symbolize the results of the interface intensity assessment.

Reversibility. The effort to reverse, or to disconnect, an interface can serve as a proxy for its reversibility. This effort depends on two factors: the difficulty to physically disconnect the interface, and the interface's position in the overall product architecture. Both dimensions are qualitatively measured using a three-point scale. As with the intensity assessment, the results are aggregated on a per function basis.

The interface reversibility of the conventional door is low across all functions. This is a result of the process that is used for assembly. Welding creates connections that can be disconnected only with great effort. As a consequence, the reversibility is low. While this is also true for most of the components of the extrusion frame door, it is not true for its outer panel. The outer panel is attached to the extrusion frame with a snap-fit connection that can be disconnected with little effort. The triangles on the vertical axes of Fig. 5 and Fig. 6 illustrate the aggregated assessment.

Standardization. Some researchers have used different types of interfaces to categorize types of modularity like swapping, sharing, bus, and sectional [13], [8], [12]. In contrast, we argue that the extent to which an interface allows different kinds of interchangeability is a matter of perspective, i.e., the level of standardization can be different for either component that is involved in the interface. We measure the standardization level as a function of the number of alternatives that exist on either side of the interface.

An assessment of the standardization level of the conventional door, measured per function, reveals that due to their geometric specificity most components exhibit a very low level of standardization. The likelihood is low that any of them can be used in another product of its class or family, or that it can accommodate components from other members of the product family. A similar result characterizes the standardization level of most components of the extrusion frame door. A slightly higher level of standardization has been assigned only to the outer panel. Its connection to the rest of the product occurs at only three points and, therefore, is geometrically less constraining than a line or even area-shaped one. The squares on the vertical axes in Fig. 5 and Fig. 6 illustrate the standardization assessment.

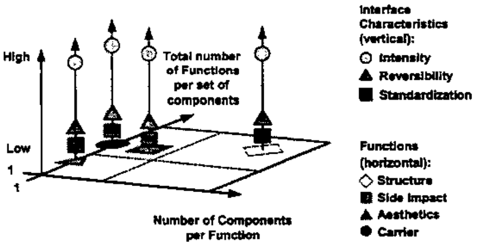

Fig. 5: Product architecture map (conventional door)

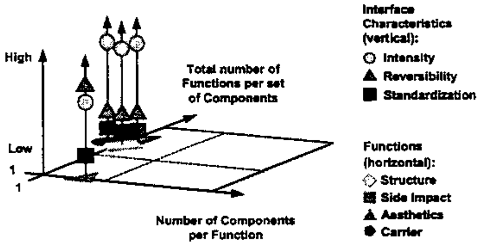

Fig. 6: Product architecture map (extrus. frame door)

The results of the product architecture analysis can be portrayed with help of product architecture maps. These maps show in their x-y plane how the functions are allocated to the components. Independent from that, and independent of each other, the different interface dimensions are shown along the vertical axis (z) (see Fig. 5 and Fig. 6).

B. *Cost Analysis / Estimation*

Once the product architectures have been described in all dimensions, the second step is to estimate the costs relevant for the analysis. To determine the costs' relevance, two boundaries have to be drawn: (1) beginning, end, and steps of the supply chain, and (2) the extent to which indirect costs are included in the analysis. This study encompasses the supply chain steps: parts manufacturing, assembly, and paint, with storage and transportation attached to each step. The cost estimations include variable costs for material, labor, and energy, as well as fixed costs for machinery, tooling, building, maintenance, and overhead. The activity-based costing philosophy applied here treats some of the fixed costs like variable costs. Exogenous factors like wages, working hours, and taxes represent average values of a developed country environment. The production program baseline is set at 5 years and 100,000 units annual production.

C. *Linking Product Architecture Features and Cost*

Two examples of the linkages between product architecture and cost are presented as illustrative examples.

1. *Linkage Analysis I ("Parts commonality")*

It is often claimed that modularity offers the potential for using one module in several members of a product family or in several product generations. As a result, the module enjoys larger economies of scale than the rest of the product. The multiple use of some fraction of a product requires two architectural aspects to be fulfilled. First, the function/component allocation scheme has to allocate the function that will be common into one chunk. Second, at least on one side of the relevant interface, there must exist a population that provides alternatives.

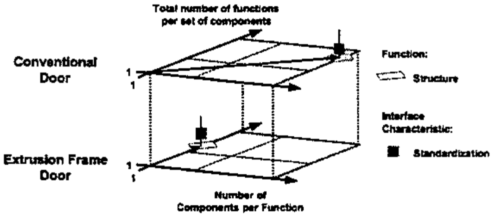

Fig. 7: Product architecture assessment for parts commonality strategy

Assuming that the aesthetic appearance on the outside is what drives changes of a car door, the structure on the inside is what one would want to keep identical across a product family or subsequent product generations. The architectural analysis of the two designs reveals that the function *structure* is much easier to isolate in case of the extrusion frame door compared to the conventional door. In addition, due to only three attachment points between frame and outer panel at the extrusion frame door, the outer panel can be more easily changed from one generation to the next than the one of the conventional door, which is attached along the entire circumference. Thus, the standardization level for the extrusion frame door with respect to the *structure* is assessed higher than for the conventional door (Fig. 7).

The difference in function isolation of the two door designs impacts their comparative cost positions. Together with process-specific dynamics, the architectural features cause the cost of the designs to exhibit different sensitivities to changes in the baseline production program. Assume that the structure of the door is in production for the full 5 years, while a face-lift occurs halfway through the product's production life, i.e., after 2.5 years. In other words, the outer panels have only half the production life times. For the two example doors, this means that the cross-over point, i.e., the point at which both designs are equally cost effective, shifts from 85,000 per year to 110,000 units per year. The range in which the extrusion frame door can be considered advantageous increases by 25,000 units (Fig. 8).

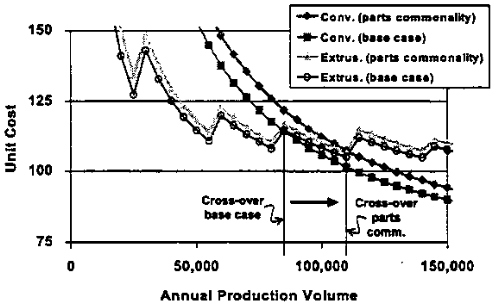

Fig. 8: Cross-over points

For a parts commonality strategy, the product architecture characteristic *function-component allocation scheme* is relevant since it translates into the fraction of the product that actually benefits from scale economies, and the interface characteristic *standardization* determines the magnitude of this advantage.

2. *Linkage Analysis II ("Postponement")*

The second linkage example focuses on logistics cost. Modularity's potential for savings of WIP costs is that of risk pooling, i.e., the total number of stocked components that are used by multiple products can be lower compared to distinct components. For this example we focus on storage and inventory costs of the third step in the supply chain, i.e., finished goods. Product variety is introduced by offering the end product in two colors.

Two product architecture features require particular attention for a postponement strategy: function-component allocation and interface reversibility; the latter because it enables the re-sequencing of production processes. The two door designs differ relatively little with respect to the way the function *aesthetic appearance* is allocated to components (in both cases, the function is delivered by one or two components only), but exhibit significant differences with respect to the interface characteristic *reversibility,* because of the snap-fit connection of the outer panel of the extrusion frame door, compared to the conventional door's welded connection (Fig. 9).

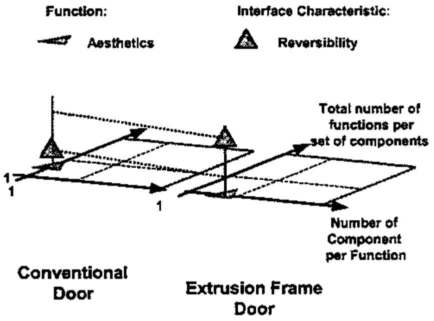

Fig. 9: Postponement strategy

As a consequence, risk pooling of the non variety-carrying portion, i.e., everything but the outside, is not possible in case of the conventional door. In case of the extrusion frame door, the frame can be pooled for both color variants and only the outer panel is stored in individual colors. Calculations using a model developed by Baker et al. [2] demonstrate the saving potential for selected service levels, assuming the product consists of one common component and one variant-specific component (Fig. 10).

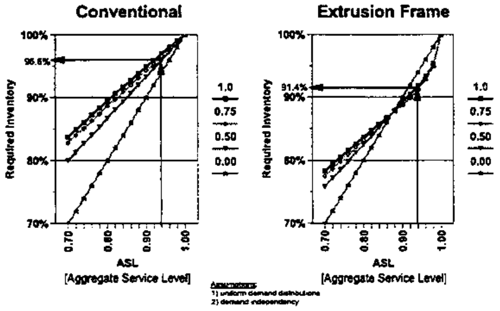

Fig. 10: Potential inventory savings

The true savings need to be adjusted for value differences between the components. The extrusion frame represents 83.3% of the total door's value, the outer panel stands for the remaining 16.7%. Adjusted for these value differences, the extrusion frame door allows for the reduction of the finished goods inventory by 42.8% through risk pooling.

V. CONCLUSION

Modularity has been proposed as a strategy that provides simultaneously multiple advantages. In contrast, we argue that modularity is actually a bundle of product architecture characteristics, and that it is advantageous to understand them and their cost effects in more detail.

The product architecture assessment framework developed in this research can be used as a guideline to help focusing the design decision making process on those variables critical for the product under consideration. For an existing product strategy (or cost reduction goals), it can help to identify the architectural features that best serve that strategy. If, for example, scale sensitive parts fabrication costs are the concern, function allocation and interface standardization should be the focus. If, on the other hand, inventory costs represent the most relevant costs, interfaces reversibility becomes a critical design dimension.

While the precise shape of the cost curves and the magnitude of cost saving or penalty effects are also process-specific, it appears to be advantageous, rather than promoting 'modularity' across the board as an optimal strategy, to better understand the structural relationships between product architecture design decisions and economic consequences. The methodology presented here is a step in this direction.

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