Product Architecture Design for Global Performance

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ABSTRACT

In this paper, I characterize the impact of product global performance on the choice of product architecture during the product development process. I classify product architectures into three categories: modular, hybrid, and integral. Existing researches show that the choice of product architecture during the new product development is a crucially strategic decision for a manufacturing firm. However no single architecture is optimal in all cases, thus analytic models are required to identify and discuss specific trade-offs associated with the choice of the optimal architecture under different circumstance. This paper develops analytic models whose objectives are obtaining global performance of product through a modular/hybrid/integral architecture. Trade-offs between costs and expected benefits from different product architectures are analyzed and compared. Multifunction products and small size are used as examples to formalize the models and show the impact of the global performance characteristics. I also investigate how optimal architecture changes in response to the exogenous costs of system integrators. Some empirical implications obtained from this study show that if one considers global performance, modular architecture is an absolutely sub-optimal decision and integral architecture is an all-the-time candidate for optimal architecture.

Keywords: Product architecture; Product development; Integrality; Modularity; Tradeoff.

INTRODUCTION

Ulrich (1995) defines product architecture explicitly as follows. (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components. There are two types of product architectures, i.e. modularity and integrality. In a modular architecture, the mapping from functional elements to physical components is one-to-one and the interfaces among interacting physical components are loosely coupled. Most components of a modular product are interchangeable and the interfaces are standardized. Good examples of modular products include desktop computers, and bicycles. Great benefits of modular architecture include products variety, components commonality, upgradability, and others. In spite of the mentioned advantages, modular architecture can only achieve local performance optimization. Global performance can only be optimized through an integral architecture. In an integral architecture, the mapping from functional elements to physical components is non one-to-one and the interfaces among interacting physical components are often tightly coupled.

For an integral product, a change in some functional element or component will lead a change to other components in order for the overall product to work correctly. Good examples of integral products include luxurious motorcycles, game software, and automobiles. Since no single architecture is optimal in all cases, analytic models are required to identify and discuss specific trade-offs associated with the choice of the optimal architecture under different circumstances.

In this paper, I develop a model to discuss a focused problem relative to the choice of product architecture. The objective of the model is to obtain global product performance through a modular/hybrid/integral product architecture. Trade-offs between costs and possible benefits from different product architectures are analyzed and compared. The researched problem in this paper is a special case of the question "Which global performance characteristics are of great value to customers and can therefore be optimized through an integral architecture?" (Ulrich, 1995). A detailed empirical study about product architecture can be found in Fujimoto (2004).

THE RESEARCH PROBLEM

Ulrich (1995) defines product performance as how well the product implements its functional elements. Some typical product performance characteristics include mass, size, speed, life and others. There are two types of product performance characteristics, i.e. local performance characteristics and global performance characteristics. Local performance characteristics relate only with partial components of a product and can be optimized through a modular architecture. For example, the speed of a computer is mainly determined by the ability of one component, i.e. CPU. In contrast, global performance characteristics relate with most of components of a product and can only be optimized through an integral architecture. For example, mass or/and size of a product are determined by almost every component within the product. Function sharing and geometric nesting are design strategies that are frequently employed to minimize mass and/or size (Ulrich, 1995). This paper studies a special case of the geometric nesting strategy.

The problem considered in this paper is a multifunction product design problem. I define multifunction product here as a device that performs a variety of functions that would otherwise be carried out by separate single-function devices. Following this definition, a multifunction product at least performs two functions. In fact, a multifunction product is developed as a combination of several single-function products. Good examples of such multifunction products include the DVD/VCR/HDD video recorder, PC/CRT/Printer combo, DVD/VCR/CRT-TV combo, multifunction peripheral, and others.

The characteristics of the architecture of a typical multifunction product are as follows. (1). Mapping from functional elements to physical components: Each component only implements a functional element. Thus, the mapping from functional elements to physical components is one-to-one. (2). Every interface is either decoupled or coupled. Moreover, if the number of the physical components in a multifunction product is M, then the number of interfaces within the product is at least$M-1$ (when components are connected as a string by the interfaces) and at most $M(M-1)/2$ (when every pair of components holds a interface between them). Size is an important performance characteristic for a lot of multifunction products. Size is typically a global performance characteristic and can only be optimized through an integral architecture. A frequently employed design strategy for minimizing the size of a product is geometric nesting. "Geometric nesting is a design strategy for efficient use of space and material and involves the interleaving and arrangement of components such that they occupy the minimum volume possible, or, in some cases, such that they occupy a volume with a particular desired shape". However, geometric nesting inevitably incurs the coupling of the interfaces between components, which often increases the costs of the product, particularly in the processes of product design and production. Therefore, optimizing global performance can get additional benefits but will also increase product costs. In this paper, I formalize and analyze each of these proprietary geometric nesting strategies, and identify optimal choice for product architectures under different costs conditions.

THE MODELS

Assumption 1: For every interface in a multifunction product, if the two physical components that are connected by this interface are geometrically nested, then the interface is coupled; Otherwise, the interface is decoupled.

Two-functions products

A two-functions product is developed from two single-function products. Each single-product serves as a component and implements a function within the two-functions product. The two components can be geometrically nested or not. For example, consider two components in Figure 1, a two-functions product can be developed from these two components without geometric nesting (see Figure 2). In Figure 2, the product architecture is modular. A good example of this type is a VHS/CRT-TV combo. On the other hand, minimizing the size of the two-functions product will obtain additional benefits (i.e. global performance). Thus, component 1 is redesigned into a specific shape to fit the second component. In this way, the two components occupy the minimum space (see Figure 3). The product architecture is integral. A good example of this type is a DVD/LCD-TV combo (see Figure 4).

Assume that by using geometric nesting, the costs of the geometric nesting is C, and the probability of realization of the geometric nesting is p, also suppose that the benefits brought by geometric nesting is E. On the other hand, if the new product adopts a modular architecture without geometric nesting, then both the benefit and cost are 0. Thus, the revenue from this product is as follows.

$$R1 = \max\{pE - C, 0\} \quad (1)$$

Three-functions products

A three-functions product holds at least two and at most three interfaces. I discuss both of them in the following subsections. For every interface within a product, there exist and only exist two design strategies: geometric nesting or not. Thus, if there are n interfaces within a product, the number of design strategies is 2^n.

Products with two interfaces

There are four (2*2) design strategies for products with two interfaces: modular, hybrid, and integral. Examples are given in Figure 5.

I denote the interface between components i and j by Iij . I also denote the design strategy for Iij by Iij(cou), and suppose Iij(cou)=1 if Iij is coupled (i.e. components i and j are geometrically nested) and Iij(cou)=0 if Iij is decoupled.

For the product with two interfaces, there are usually two system integrators (SI-s), one for each interface. They handle the projects of geometric nesting. Suppose that the probabilities of realizations of the two geometric nestings are p1, p2 respectively. For tractability, I assume that the costs of both SI-s are identical, as C respectively, and also the expected benefits from both geometric nestings are identical, as E respectively.

$$R2 = \max\{(p1 + p2)E - 2C,\ p1E - C,\ p2E - C,\ 0\} \quad (2)$$

Products with three interfaces

There are eight (2*2*2) design strategies for products with three interfaces: one modular (neither interface is geometrically nested), one integral (all interfaces are geometrically nested), and six hybrids (some, but not all interface are geometrically nested). The details are as follows:

(I12(cou),I23(cou),I13(cou))=
(0,0,0),(0,0,1), (0,1,1),(0,1,0),(1,0,0),(1,1,0),(1,0,1),(1,1,1)

The eight design strategies can be modeled theoretically like model (2) in section 3.2.1. However, rather than constructing theoretical models, I consider a more practical product development process.

Assumption 2: The global performance can only be obtained if at least the two strongly related interfaces are geometrically nested.

I denote the benefits of the global performance by T. The nestings of the first and second interfaces can be generated by two SI-s or a heavy system integrator (HSI). All these jobs related to the generation of the third interface and integration of the whole product system are usually performed by HSI. Suppose that the probability of realizing geometric nesting of interface 3 is p3, and suppose that the costs of the HSI is Cs. I assume that T > Cs > C, E > W, and both p1, p2 >> p3.

HSI only:

$$R3 = \max\{(p1 + p2)E + p3W + p1p2T - Cs, 0\} \quad (3)$$

HSI and a SI only:

$$R4 = p1E - C + p1\max\{p2E + p3W + p2T - Cs, 0\} + (1-p1)\max\{p2E + p3W - Cs, 0\} \quad (4)$$

$$R5 = p2E - C + p2\max\{p1E + p3W + p1T - Cs, 0\} + (1 - p2)\max\{p1E + p3W - Cs, 0\} \quad (5)$$

HSI and both SI-s:

$$R6 = p1E + p2E - 2C + p1p2(p3W + T - Cs) + (1 - p1p2)\max(p3W - Cs, 0) \quad (6)$$

COMPARISONS AND IMPLICATIONS

Without loss generality, assume that p1 > p2.

Three-functions products with two interfaces

The cost of a SI, i.e. C, must be a value within one of the following three intervals.
$0 <= C < p2E$; $p2E<= C < p1E$; $p1E <= C < \infty$.

Proposition 1.
If $0 <= C < p2E$, select integral architecture;
If $p2E <= C < p1E$, select hybrid architecture, i.e. Hybrid-I in Figure 5;
If $p1E <= C < \infty$, select modular architecture.

Three-functions products with three interfaces

Assume that the global performance benefit T is large enough, i.e. T >> E, to make that $p2(1 - p1)T > p1E$ possible. Thus, $p2E + p2T > p1E + p2E + p1p2T$.

According to the above assumption, the cost of HSI, i.e. Cs, must be a value within one of the following six intervals.

$0 <= Cs < p2E$; $p2E <= Cs < p1E$; $p1E <= Cs < p1E + p2E + p1p2T$; $p1E + p2E + p1p2T <= Cs < p2E + p2T$; $p2E + p2T <= Cs < p1E + p1T$; $p1E + p1T <= Cs < \infty$.

To simplify the analysis, I ignore the term of p3W. Assume that if both interfaces 1 and 2 are geometrically nested, then the product architecture is integral. On the other hand, if neither of them is geometrically nested, then the product architecture is modular. Otherwise, the product architecture is hybrid.

Proposition 2. Assume $0 <= Cs < p2E$.
Select integral architecture, and
If $2C < W1$, using all three integrators to realize it (i.e. R6), where $W1 = Cs(1 - p1p2)$;
Otherwise, using HSI only to realize it (i.e. R3).

Proposition 3. Assume $p2E <= Cs < p1E$.
If $2C < \min\{W1, W2\}$, use all three integrators to realize integral architecture (R6).
where $W2 = 2p2E - 2p1p2Cs - 2p1p2E + 2p1Cs$;
If $2C > \max\{W1, W3\}$, use HSI only to realize integral architecture (R3).
where $W3 = 2p1p2E - 2p2E + 2Cs(1 - p1)$;
Otherwise, use a SI to realize the first interface firstly, then use HSI to realize integral architecture (R4).

Proposition 4. Assume $p1E <= Cs < p1E + p2E + p1p2T$.
If $2C < \min\{W1, W4, W2\}$, use all three integrators to realize integral architecture (R6).
where $W4 = 2p1E - 2p1p2Cs - 2p1p2E + 2p2Cs$;
If $2C > \max\{W1, W5, W3\}$, use HSI only to realize integral architecture (R3).
where $W5 = 2p1p2E - 2p1E + 2Cs(1 - p2)$;
If $W2 < 2Co < W3$ and $Cs < E$, use a SI to realize the first interface firstly, then use HSI to realize integral architecture (R4);
Otherwise, use a SI to realize the second interface firstly, then use HSI to realize integral architecture (R5).

Proposition 5. Assume $p1E + p2E + p1p2T <= Cs < p2E + p2T$.
If $2C < \min\{W2, W4\}$, use all three integrators to realize integral architecture (R6);
If $2C > W2$ and $Cs < E$, use a SI to realize the first interface firstly, then use HSI to realize integral architecture (R4);
Otherwise, use a SI to realize the second interface firstly, then use HSI to realize integral architecture (R5).

Proposition 6. Assume $p2E + p2T <= Cs < p1E + p1T$.
If $2C < \min\{W4, W6\}$, use all three integrators to realize integral architecture (R6).
where $W6 = 2p2E + 2p1p2(T - Cs)$;
If $2C > W4$ and $Cs < W7$, use a SI to realize the second interface firstly, then use HSI to realize integral architecture (R5).
where $W7 = (p2E - p1E + p2(p1E + p1T))/p2$;
Otherwise, select a hybrid architecture: use a SI only to realize the first interface (R4).

Proposition 7. Assume $p1E + p1T <= Cs < \infty$.
If $2C < W6$, use all three integrators to realize integral architecture (R6);
Otherwise, select a hybrid architecture: use a SI only to realize the first interface (R4).

IMPLICATIONS

I consider some of the empirical implications obtained from the comparative analysis in the prior sections.

Corollary 1. There is no single architecture which is optimal in all cases, whereas there are architectures that are always sub-optimal.

Corollary 2. Under consideration of the global performance, modular architecture is an absolutely sub-optimal decision.
Corollary 2 can simply be verified by checking Propositions 2-7, among them, modular architecture is never a candidate for optimal architecture.

Corollary 3. To obtain global performance, achieving integral architecture is an all-the-time candidate for optimal architecture.

Corollary 4. If the global performance benefit T is sufficiently large, then using a HSI to reap it is always an optimal decision.

The models developed in this paper are only dedicated to products which have a simple architecture structure, for example, multifunction products. Therefore, I suggest future researches on models which can analyze products that have a complex architecture structure, for example, automobiles.

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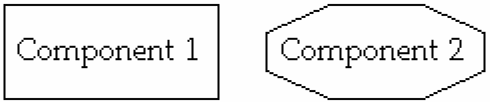

Figure 1. An example of two components

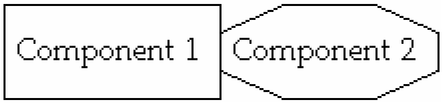

Figure 2. An example of two-functions product in modular architecture

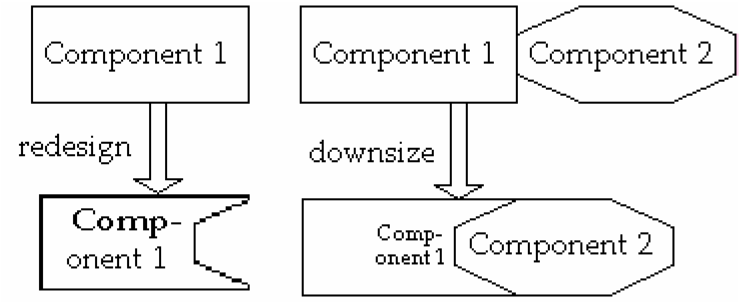

Figure 3. Redesign process from modular to integral architecture

Figure 4. An example of two-functions product in integral architecture

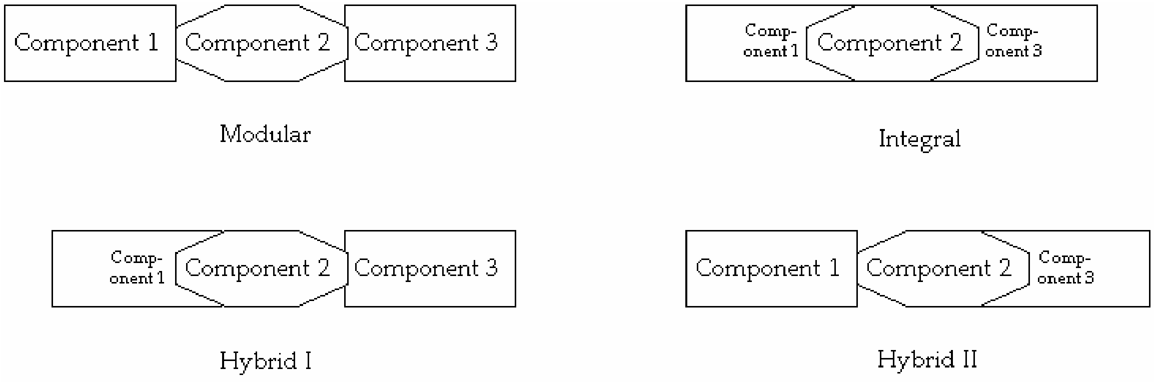

Figure 5. An example of three-functions product