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The Role of Product Architecture in the Manufacturing Firm

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Abstract

Product architecture is the scheme by which the function of a product is allocated to physical components. This paper further defines product architecture, provides a typology of product architectures, and articulates the potential linkages between the architecture of the product and six issues of managerial importance: (1) product variety, (2) product performance, (3) component standardization, (4) design and production lead time, (5) product change, and (6) the organizational structure of the firm. The paper is conceptual and foundational, synthesizing fragments from several different disciplines, including software engineering, design theory, operations management, and product development management. The paper is intended to raise awareness of the far-reaching implications of the architecture of the product, to create a vocabulary for discussing and addressing the decisions and issues that are linked to product architecture, and to identify and discuss specific trade-offs associated with the choice of a product architecture.

Key words: product architecture, modularity, design, components, variety, commonality, standardization, product development, manufacturing.

1. Introduction

Both universities and industry have placed renewed emphasis on manufacturing [Berger et al 1989]. Issues of current interest include: product quality, both in terms of the precision with which the production system conforms to the design specifications and in terms of ultimate customer satisfaction; product variety and the ability of the firm to offer a product precisely tuned to specific customer needs; lead time for both product development and production; frequency of new product introduction and model refinements; rationalization of the product line through component standardization and improved product positioning; and effective relationships between manufacturing firms and their suppliers and product development partners. For example, Clark and Fujimoto (1991) emphasize these topics in their study of the world automobile industry, and the recently articulated notion of *lean production* includes many of these dimensions of manufacturing performance [Womack et al 1990] .

A common element relating all of these issues is the product itself. Some connections between the product and the performance of the manufacturing firm are widely accepted. For example, the philosophy behind Taguchi methods and other approaches to *robust* product design is that product design parameters can be chosen to maximize product reliability and eliminate performance variability [Taguchi and Clausing 1990]. The *design for manufacturing* movement is based on the idea that the piece parts and assemblies of a product can be designed such that the cost and quality of the product leaving the production system are improved [Daetz 1987, Whitney 1988]. And advocates of *Quality Function Deployment* argue that to achieve high customer satisfaction the technical performance characteristics of the product must be driven by the *voice of the customer* [Hauser and Clausing 1988].

This paper argues that the *architecture* of the product can be a key driver of the performance of the manufacturing firm, that firms have substantial latitude in choosing a product architecture, and that the architecture of the product is therefore important in managerial decision making. The paper builds on knowledge from several somewhat disparate research communities: design theory, software engineering, operations management, and management of product development. My approach is to synthesize fragments of existing theory and knowledge into a new framework for understanding product architecture, and to use this framework to illuminate, with examples, how the architecture of the product relates to manufacturing. My intention is that industrial practitioners will benefit from the argument and develop a stronger conceptual foundation for decision making, and that researchers will benefit from the argument by an enhanced ability to formulate focused research questions around these issues.

I divide the paper into five remaining sections. Section 2 defines product architecture. Section 3 provides a typology of architectures. Section 4 shows how product architecture and production system flexibility combine to enable product variety. Section 5 identifies and discusses the potential linkages between the architecture of the product and five other issues of managerial importance: product performance, component standardization, design and production lead time, product change, and the organizational structure of the firm. Finally, section 6 includes a summary of the key points of the paper and a discussion of several promising research directions.

2. What is Product Architecture?

In informal terms, the architecture of the product is the scheme by which the function of the product is mapped onto physical components. I define product architecture more precisely as:

1. The arrangement of *functional elements.*
2. The mapping from *functional elements* to *physical components.*
3. The specification of the *interfaces* between interacting physical components.

This section expands on this definition using the example of a *trailer* to illustrate the key points.

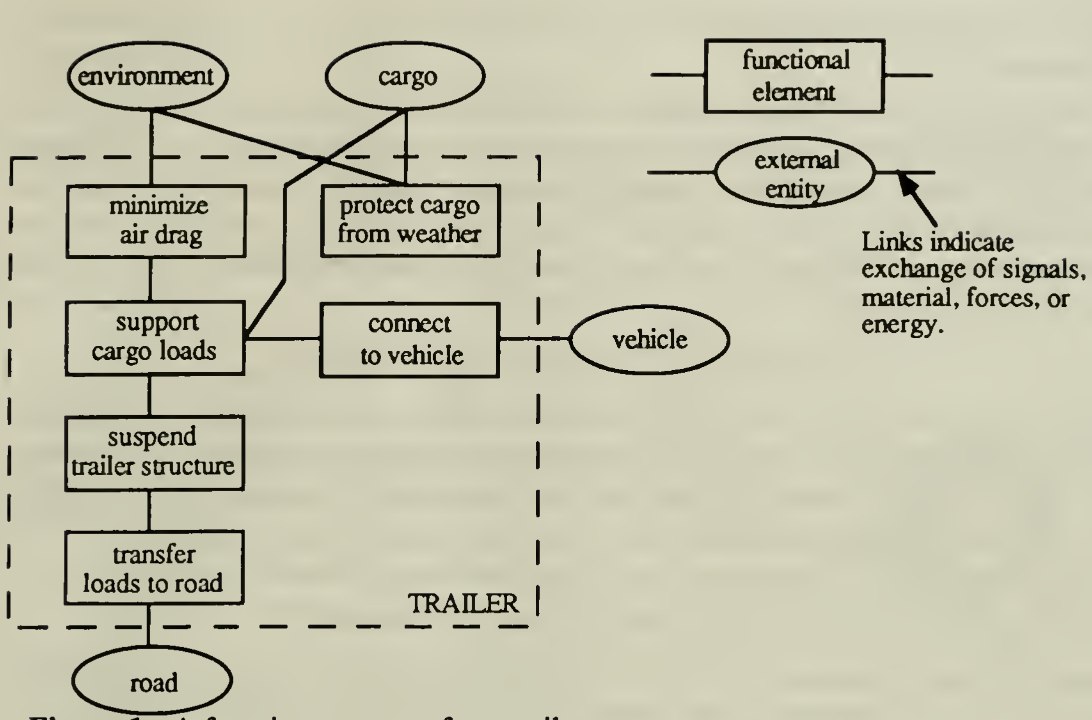
2.1 The Arrangement of Functional Elements

The function of a product is *what it does* as opposed to what the physical characteristics of the product are. There have been several attempts in the design theory community to create formal languages for describing function [Finger and Dixon 1989], and there have been modest successes in narrow domains of application such as electro- and fluid-mechanical systems and digital circuits [Ulrich and Seering 1989]. There have also been efforts to create informal functional languages to facilitate the practice of design [Pahl and Beitz 1984, Hubka and Eder 1988]. These languages are frequently used to create diagrams consisting of functional elements, expressed as linguistic terms like "convert energy", connected by links indicating the exchange of signals, materials, forces and energy. Some authors of informal functional languages provide a vocabulary of standard functional elements, while others rely on users to devise their own. Functional elements are sometimes called *functional requirements* [Suh 1990] or *functives* [Fowler 1990], and the function structure has been variously called a *functional description* and a *schematic description* [Ulrich and Seering 1989]. Consistent with Pahl and Beitz, and Hubka and Eder, I call the arrangement of functional elements and their interconnections a *function structure.* An example function structure for a trailer is shown in figure 1.

Function structures can be created at different levels of abstraction. At the most general level, the function structure for a trailer might consist of a single functional element "Expand cargo capacity." At a more detailed level, the function structure could be specified as consisting of the collection of functional elements shown in figure 1: *connect to vehicle*, *protect cargo from weather*, *minimize air drag*, *support cargo loads*, *suspend trailer structure*, and *transfer loads to road* [Fowler 1990].

As they are expressed in more detail, function structures embody more assumptions about the physical working principles on which the product is based. For example, *expand cargo capacity* does not assume the trailer will be a device towed over the road (the trailer could be a lighter-than-air craft), while the more detailed function structure shown in figure 1 does embody this assumption. For this reason, two products that at the most general level do the same thing may have different function structures when described at a more detailed level [O'Shaugnessy and Sturges 1992].

While most functional elements involve the exchange of signals, materials, forces, and energy, some elements do not interact at all with other functional elements. An example of such an element might be *harmonize aesthetically with vehicle.*



Links indicate exchange of signals, material, forces, or energy.

Figure 1: A function structure for a trailer.

2.2 The Mapping from Functional Elements to Physical Components

The second part of the product architecture is the mapping from functional elements to physical components. A discrete physical product consists of one or more components. For clarity, I define a component as a separable physical part or subassembly, however for many of the arguments in the paper, a component can be thought of as any distinct region of the product, allowing the inclusion of a software subroutine in the definition of a component. Similarly, distinct regions of an integrated circuit, although not actually separate physical parts, could be thought of as components.

Physical components implement the functional elements of the product. The mapping between functional elements and components may be one-to-one, many-to-one, or one-to-many. Two different trailer designs and their associated mappings of functional elements to components are shown in figure 2.

2.3 The Specification of the Interfaces between Interacting Physical Components

By definition, interacting components are connected by some physical interface. Interfaces may involve geometric connections between two components, as with a gear on a shaft, or may involve non-contact interactions, as with the infrared communication link between a remote control and a television set. An interface specification defines the mating geometry in cases where there is a geometric connection, and defines the protocol for the primary interactions across the component interfaces.

For example, one of the interfaces for the trailer shown in figure 2 is between the box and the bed. The specification of the interface includes the dimensions of the contact surfaces between the two components, the positions and sizes of the bolt holes, and the maximum force the interface is expected to sustain.

Note that interfaces may be specified to adhere to a standard protocol. Examples of protocols that have been standardized across many different manufacturers' products are: SCSI (small computer systems interface), tire/rim standards for automobiles, a stereo "phono" jack, a garden hose connection thread, and a "ball-type" trailer hitch . Manufacturers sometimes choose to create proprietary interfaces within their products, but may adopt a standard protocol for interfaces used within their own product line.

3. A Typology of Product Architectures

The first distinction in the typology is between a *modular* architecture and an *integral* architecture. 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.

3.1 Types of Mappings from Functional Elements to Physical Components

The two trailers in figure 2 illustrate two extreme examples of mappings from functional elements to components. One trailer embodies a one-to-one mapping between functional elements and components. Assuming that the component interfaces are de-coupled (more on this later), this trailer has a modular architecture. In the field of software engineering, the notion of module *cohesion* or *strength* is similar to the one-to-one mapping of functional elements to components (Schach 1990). The other trailer embodies a mapping in which several functional elements each are implemented by more than one component, and in which several components each implement more than one functional element (a complex mapping). This trailer has an integral architecture. The phenomenon of a single component implementing several functional elements is called *function sharing* in the design theory community and is described in detail by [Ulrich and Seering 1990].

To some extent, whether or not functional elements map to more than one component depends on the level of detail at which the components and functional elements are considered. For example, if every washer, screw, and filament of wire is considered a component, then each functional element will map to many components. In order to more precisely define what a one-to-one mapping between functional elements and components means, consider a product disassembled to the level of individual piece parts. (This level of disassembly has been called the *iota* level[1].) In general, many possible subassemblies[2] could be created from these iota parts. If there is a partitioning of the set of iota parts into subassemblies such that there is a one-to-one mapping between these subassemblies and functional elements, then the product exhibits the one-to-one mapping characteristic of a modular architecture.

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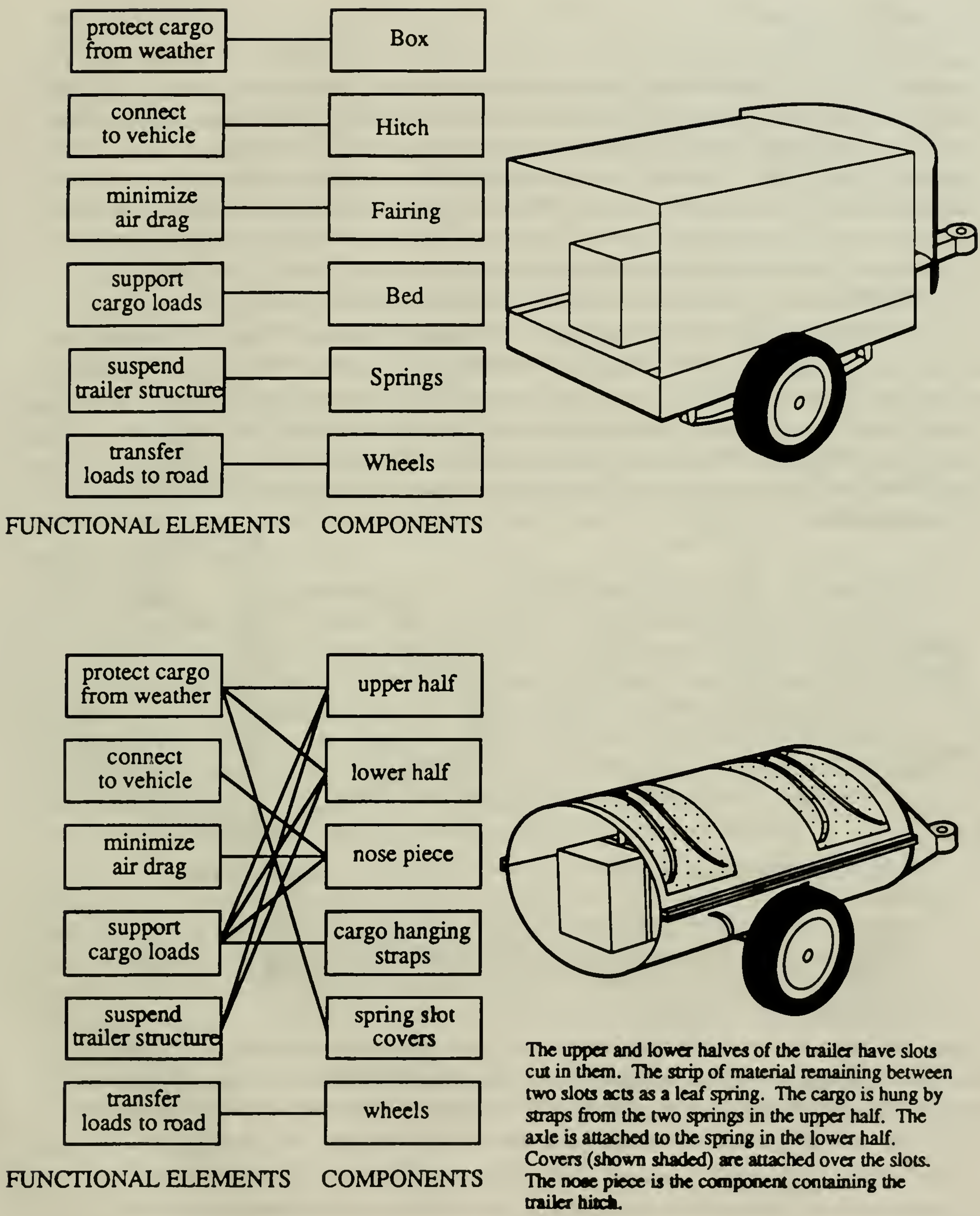
[1] I have seen this term used at the General Motors Vehicle Assessment Center to describe the parts resulting from a complete disassembly of a vehicle, down to the last nut, bolt, and washer.

[2] A subassembly is a collection of components that (1) can be assembled into a unit and (2) can be subsequently treated as a single component during further assembly of the product.



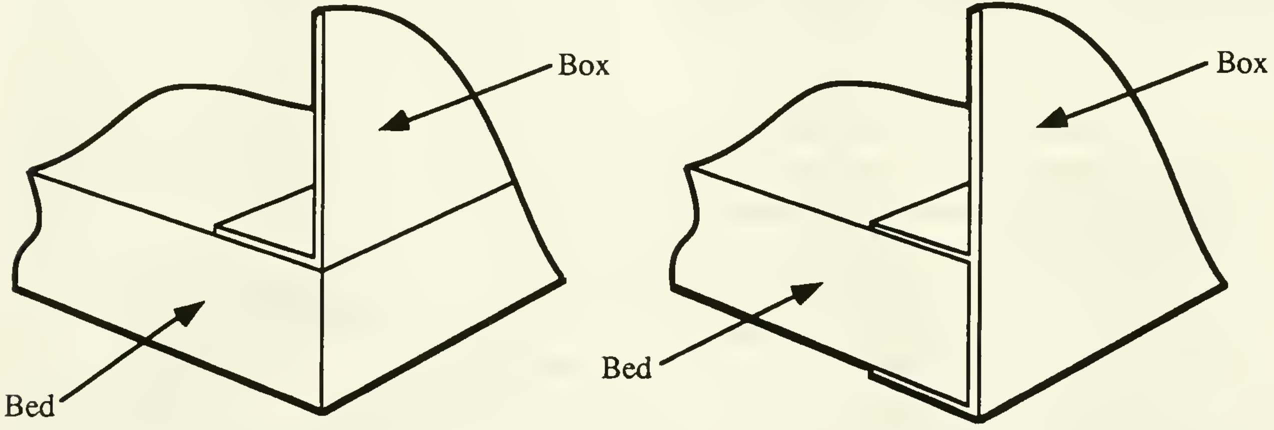
The upper and lower halves of the trailer have slots cut in them. The strip of material remaining between two slots acts as a leaf spring. The cargo is hung by straps from the two springs in the upper half. The axle is attached to the spring in the lower half. Covers (shown shaded) are attached over the slots. The nose piece is the component containing the trailer hitch.

Figure 2: Two example mappings of functional elements to physical components.

3.2 Interface Coupling

In addition to one-to-one mappings, modular architectures include de-coupled component interfaces. Two components are coupled if a change made to one component requires a change to the other component in order for the overall product to work correctly. Two physical components connected by an interface are almost always coupled to some extent; there is almost always a change that can be made to one component that will require a change to the other component. (For example, arbitrarily increasing the operating temperature of one component by 1000C will require a change to nearly any imaginable neighboring component.) However, in practical terms, coupling is relevant only to changes that modify the component in some useful way. (See [Schach 1990] for a detailed discussion of the different types of coupling encountered in software.)

Figure 3 illustrates an example of an interface between two components, the bed and the box from the first trailer in figure 2. The coupled interface embodies a dependency between the thickness of the bed and the vertical gap in the box connection slot. The de-coupled interface involves no such dependency. For the coupled interface, when the thickness of the bed must be changed to accommodate a change in the cargo load rating, the box must change as well. Although the example in figure 3 is geometric, coupling may also be based on other physical phenomena such as heat or magnetism.



De-coupled Interface

Coupled Interface

Figure 3: Two example interfaces between the trailer box and trailer bed; one de-coupled, the other coupled. The coupled interface requires that the box be changed whenever a change in the thickness of the bed is made to accommodate increased structural loading.

3.3 Types of Modular Architectures

I divide modular architectures into three sub-types: *slot*, *bus*, and *sectional*. Because each of the three sub-types is modular, each embodies a one-to-one mapping between functional elements and components, and the component interfaces are de-coupled; the differences among these sub-types lie in the way the component interactions are organized.

Slot. Each of the interfaces between components in a *slot* architecture is of a different type from the others, so the various components in the product can not be interchanged. An automobile radio is an example of a component in a slot architecture. The radio implements exactly one function and is de-coupled from surrounding components, but its interface is different from any of the other components in the vehicle (e.g. radios and speedometers have different types of interfaces to the instrument panel.)

Bus. In a bus architecture, there is a common *bus* to which the other physical components connect via the same type of interface. A common example of a component in a bus architecture would be an expansion card for a personal computer. Non-electronic products can also be built around a bus architecture. Track lighting, shelving systems with rails, and adjustable roof racks for automobiles all embody a bus architecture. I also include components connected by a multi-dimensional network in the bus sub-type.

Sectional. In a sectional architecture, all interfaces are of the same type and there is no single element to which all the other components attach. The assembly is built up by connecting the components to each other via identical interfaces. Many piping systems adhere to a sectional architecture, as do sectional sofas, office partitions, and some computer systems.

Figure 4 illustrates this typology for the trailer example, for a desk, and for a personal computer. I intend for the typology to provide a vocabulary for describing different product architectures. The types I present are idealized; most real products exhibit some combination of the characteristics of several types. Products may also exhibit characteristics of different types depending on whether one observes the product at the level of the overall final assembly or at the level of individual piece parts and subassemblies.

A firm can design and manufacture products without ever explicitly creating a product architecture or even a function structure. In the domains of software and electronic systems, the idea of a function structure (labeled as a *schematic*, *flow chart*, etc.) is prevalent in industrial practice (Mead and Conway 1980, Schach 1990). However, the notion of a function structure is just beginning to be disseminated in many mechanical domains. (See for example [Ullman 1992] for a recent mechanical design textbook adopting the idea.) If a product architecture is explicitly established during the product development process, this step usually occurs during the system-level design or *systems engineering* phase of the process after the basic technological working principles have been established, but before the design of components and sub-systems has begun.

The examples in figure 4 suggest that firms possess substantial latitude in choosing a product architecture, although the architecture of many existing products may be less the result of deliberate choice and more the result of incremental evolution. Several scholars have prescribed a modular architecture as ideal. For example, Suh (1990) argues that a modular architecture is an axiom of good design, and Alexander (1964) presents an "optimal" design methodology ensuring a lack of coupling between components. (Although neither author argues his point in my terminology.) I maintain that while product architecture is extremely important, no single architecture is optimal in all cases. The balance of the paper discusses the potential linkages between the architecture of the product and a set of issues of managerial importance. A recognition and understanding of these linkages is a prerequisite to the effective choice of an architecture for a particular product.

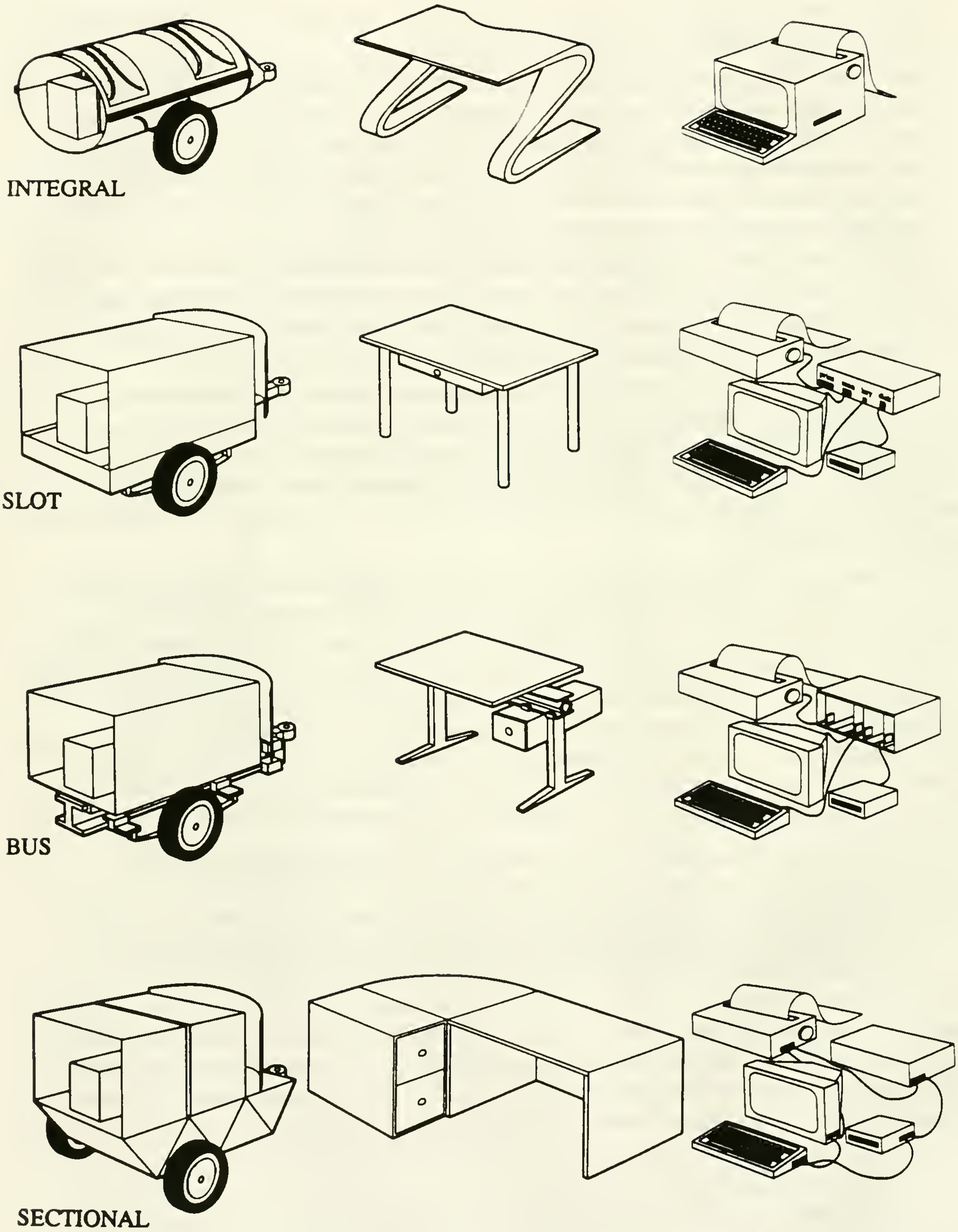


Figure 4: Examples of types of product architectures.

4. The Relationship Between Product Architecture and Product Variety

I define product variety as the diversity of products that a production system provides to the marketplace. Product variety has emerged as an important element of manufacturing competitiveness. Based on survey responses from 255 managers, Pine (1991, 1992) provides empirical evidence that both market turbulence and the need for product variety have increased substantially over the past decade and will continue to increase in the future. Variety is also one of the elements of lean production (Womack 1990). High variety can be produced by any system at some cost. For example, an auto manufacturer could create different fender shapes for each individual vehicle by creating different sets of stamping dies, each of which would be used only once. Such a system is technically feasible, but prohibitively expensive. The challenge is to create the desired product variety economically.

The ability of a firm to economically produce variety is frequently credited to manufacturing *flexibility.* (See [Suarez et al 1991] for a comprehensive review of the literature on flexibility.) When viewed at the level of the entire manufacturing system, this is a tautology— if a system is economically producing variety it is to some extent flexible. However, manufacturing flexibility is often equated with the flexibility of the process equipment in the plant (e.g. computer-numerical controlled milling machines) or with flexible assembly systems (e.g. programmable electronic chip insertion equipment). (See, for example, [Jaikumar 1986].) In this context, a flexible production process incurs small fixed costs for each output variant (e.g. low tooling costs) and small change-over costs between output variants (e.g. low set-up times). This notion of flexibility is consistent with Upton's (1991) definition: "... the ability to change or adapt with little effort, time, or penalty." I argue that much of a manufacturing system's ability to create variety resides not with the flexibility of the equipment in the factory, but with the architecture of the product. This section shows how both the flexibility of the factory production equipment and the product architecture interact to contribute to the ability to economically create product variety.

4.1 Product Architecture Determines How the Product can be Changed

Variety is only meaningful to customers if the functionality of the product varies in some way[3]. This variation may be in terms of the set of functional elements implemented by the product (Does the trailer protect the cargo from the environment at all?) or in terms of the specific performance characteristics of the product relative to a particular functional element (Is the environmental protection *normal* or *heavy duty*?). The architecture of the product determines which physical components of the product must change in order to vary the functionality of the product. At one extreme, modular products allow each functional element of the product to be changed independently by changing only the corresponding component. At the other extreme, fully integral products require changes to every component to effect change in any single functional element of the product.

Consider the trailer example. Assume customers' needs can be neatly divided in the following ways. Some customers want to minimize air drag, some do not. Two types of vehicle connection

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[3] I use the term *functionality* in a broad sense to mean how the product meets customer needs. When viewed this way, functionality could include offering style as well as providing purely technical performance.

and three alternatives for the type of environmental protection are desired. Three alternatives are also desired for both the structural load rating and for the ride quality of the suspension system[4]. Under these assumptions, if variety incurred no cost, the firm would offer 108 distinct trailers to the marketplace (2 x 2 x 3 x 3 x 3 = 108).

If the firm uses the modular product architecture shown in figure 2, each of the 108 different trailers can be created from a total of only 12 different types of components: a single type of fairing (which is either included with the trailer or not), two types of hitches, three types of boxes, three types of beds, three types of spring assemblies, and one type of wheel assembly. Because each functional element maps to exactly one physical component, and because the interfaces are de-coupled, the variety can be created by forming 108 combinations from a set of 12 component building blocks. I am not the first to observe that variety can be created by combinations of building blocks. In fact, this combinatorial approach to variety is part of a five-step technique called (somewhat confusingly) Variety Reduction Program (Suzue and Kohdate 1990). Nevins and Whitney (1989) also give several examples of such combinatorial assembly of product variants.

If the firm wishes to offer all 108 variants and uses the integral product architecture shown in figure 2, 73 different types of components will be required: 27 types of upper halves, 27 types of lower halves, 12 types of nose pieces, 3 types of cargo hanging straps, 3 types of spring slot covers, and 1 type of wheel assembly. Because in many instances each component implements several functional elements, there must be as many types of each component as there are desired combinations of the functional elements it implements. For example, to provide all of the different desired combinations of the two vehicle connection types, the two types of drag reduction, and the three load ratings, 12 distinct types of nose pieces will be required because the nose piece contributes to all three of the functional elements associated with the options.

4.2 Variety and Flexibility

At first glance, producing 108 varieties of the integral design appears to be far less economical than for the modular design. In fact, the flexibility of the production process equipment is an additional factor in determining the basic economics of producing variety. If the trailer components could only be economically produced in large lot sizes because of the large set up times required for the process equipment, or if each type of component required large tooling investments, then in fact the integral design would be very expensive to produce with high variety. High variety under these conditions would require some combination of large inventory costs, large set-up costs, or large tooling costs[5]. However, if the integral trailer components could be produced economically in small lots (e.g. set-up costs are low) and without tooling investments, then variety could be offered economically for the integral design.

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[4] Assume for the purpose of the example that the type of suspension and the load rating are independent choices. In practice, these two functional elements may in fact be related.

[5] Inventory costs and set-up costs can be traded off against one another; inventory can be minimized by using small lot sizes, but this leads to high set-up costs.

For example, consider the following production system for the integral trailer. The upper and lower halves are made by a computer controlled rolling machine followed by a computer controlled laser cutting machine. Plates of arbitrary thickness and material can be rolled to arbitrary diameters (within certain limits), and slots for the springs can be cut along arbitrary trajectories; all with small set-up times, no tooling investment, and rapid processing times. The nose piece is created by laser cutting, computer-controlled rolling, and automated welding. The six components are then assembled manually. Because of the flexibility of the upper half, lower half, and nose piece production processes, the required component types can be produced as they are needed, in arbitrary combinations, and then assembled into the required trailer types. Such process flexibility allows economical high-variety production of a product with an integral architecture.

Flexible production process hardware can also have an impact on the production of the modular design. Using inflexible processes requiring expensive tooling and large lot sizes, the 12 different components required to assemble the 108 different product variants would be held in inventory ready for final assembly. Alternatively, the components for the modular design could be produced with flexible production equipment, eliminating the need for the inventories and tooling expense.

With a modular product architecture, product variety can be achieved with or without flexible component production equipment. In relative terms, in order to economically produce high variety with an integral architecture, the component production equipment must be flexible.

This argument assumes in all cases that the final assembly process itself is somewhat flexible. That is, different combinations of components can be easily assembled to create the final product variety. This assumption is usually valid for products assembled manually, but some assembly systems, particularly high-volume automated assembly equipment, violate this assumption. For these systems, the flexibility of the final assembly process is also a key driver of the ability of the firm to offer product variety.

4.3 Infinite Variety

Many flexible production processes can be programmed to produce an *infinite* variety of components. For example, a computer-controlled laser cutting system can cut along an arbitrarily specified trajectory. This flexibility allows systems incorporating these processes to create products that can be infinitely varied with respect to one or more properties. This ability to continuously vary the properties of components by a flexible process provides a subtle distinction between the variety that can be created by assembling products from a finite set of component alternatives and the variety that can be created by flexible component production processes. Assembly from finite component choices is fundamentally a "set operation" in that it allows sets to be formed from discrete alternatives. Continuously variable process equipment can implement arbitrary mathematical relationships among component characteristics. For example, the laser cutting machine could be programmed to cut along a curve parameterized as a function of a set of other characteristics, such as expected climate of the use environment, the types of loads the trailer will carry, and the road quality in the customer's geographical region. Note that the ability to arbitrarily vary component characteristics can be achieved for both integral and modular architectures, if components are fabricated with programmable processes.

A summary of the effect of product architecture and component process flexibility on the resulting performance characteristics of the production system is shown in figure 5.

Product Architecture	Low	High
Modular	• Variety achieved by combinatorial assembly from relatively few component types. • Can assemble to order from component inventories. • Minimum order lead time dictated by final assembly process.	• May fabricate components to order as well as assemble to order. • May choose to carry component inventories to minimize order lead time. • Infinite variety is possible when components are fabricated to order.
Integral	• High variety not economically feasible; would require high fixed costs (e.g. tooling), high set-up costs, large order lead times, and/or high inventory costs.	• Variety can be achieved without relatively high inventory costs by fabricating components to order. • Minimum order lead times dictated by both component fabrication time and final assembly time. • Infinite variety is possible.

Component Process Flexibility

Figure 5: Product architecture <u>and</u> component process flexibility dictate the economics of producing variety.

5. Linkages to other Issues of Managerial Importance

The key argument of this paper is that the architecture of the product is linked to the performance of the manufacturing firm, and therefore to issues of managerial importance. Section 4 discussed how product architecture and production process flexibility relate to product variety. This section identifies and discusses the linkages between product architecture and product performance, component standardization, design and production lead time, product change, and the organization of the firm.

5.1 Product Performance

Some dimensions of product performance can be optimized only through an integral architecture. Functional elements involving noise, size, aerodynamic drag, and aesthetics (among others) are difficult to map to a single physical component; in most cases these characteristics of the product arise holistically from a collection of the physical components. For example, product mass and cost, because they are unavoidable attributes of all physical objects, are always determined by the sum of the mass and cost of each and every component, and so render certain functional elements, such as those involving acceleration, impossible to map to a single component.

Where these holistic functional elements play a dominant role in product success, a high-performance product will likely exhibit an integral architecture. Compare for example the modular architecture of a diesel truck engine, where the size, weight, and aerodynamic profile of the engine are small relative to the payload, to the integral architecture of the engine of a racing motorcycle, where each gram and cubic centimeter is critical to performance. Similarly, in passenger automobiles, support structures and bodies are most frequently integrated into a single "unit body" in an effort to reduce size, weight, and cost, and to enhance aesthetics and aerodynamics, while the support structure and body of most trucks is quite modular.

Part of the reason modular architectures do not allow for optimization of holistic performance characteristics is that these architectures incur physical redundancy or "overhead" associated with interfaces and with eliminating component coupling. Because the bus and sectional architectures incorporate a standard interface for all components, they incur even more redundancy than the slot architecture.

The linkage between product architecture and holistic dimensions of product performance provides some theoretical support for the idea of *product integrity* articulated by Clark and Fujimoto (1990).

5.2 Component Standardization

A modular product architecture enables a clear definition of the function of each component in the product and of the interface between the component and the rest of the product. The function of a component may be generic enough that a standard interface protocol can be adopted and identical components can be used in more than one type of product. This sharing of components occurs both among the products of a single manufacturer and among the products of diverse manufacturers. The potential benefits of the use of a standard component include: reduced component costs because of economies of scale in component production, enhanced component performance arising from ongoing refinement, broad amortization of product development costs, and reduced materials management costs because of a reduction in part numbers used in the production system. The potential costs of the use of a standard component include: a mismatch between ideal performance characteristics and those available in standard components, and an increase in unit costs arising from the use of a component with excess (costly) capability.

Component standardization may occur at the level of individual screws and washers in a product or may involve complex subsystems like power trains or disk drives. The choice of which functional elements to implement in a modular way and which to implement in an integral way can be driven in part by the availability and potential costs and benefits of the component standardization enabled by the mapping.

Strategic issues add complexity to the issue of component standardization. A modular design may allow a manufacturer to focus on the overall system-level design of the product and choose among the best components available to implement the details. (This appears to be the current strategy of many personal computer manufacturers.) However, a modular design may provide an opportunity for other firms to make inroads into profitable parts of the component business, as has happened with mainframe computer random-access memory. Some of these strategic issues have been explored by Langlois and Robertson (1992).

There has been some theoretical research in modeling the decisions associated with component standardization (Evans 1963, Shaftel 1971, Shaftel and Thompson 1977). In fact, the problem of what features to include in a standard subsystem to be used across a product line has been named the *Modular Design Problem* (Evans 1963) in the Operations Research community.

5.3 Design and Production Lead Time

A modular product architecture may enable a reduction in design time, because once the function of a component and its interfaces have been specified, different component design tasks can be completed by groups operating in parallel. With an integral architecture, the components must be designed to implement multiple functional elements and the coupling between components must be accommodated. This process may require coordination among several design groups and may require multiple design disciplines. Lovejoy articulates the highly non-linear theoretical reduction in complexity engendered by decomposing the design problem into de-coupled subproblems (1992). Clark provides evidence that automobile manufacturers with the shortest product development times adopt a "black box" approach to component development, in which the basic function of a component as well as its interfaces are specified, but the details of the design are not (Clark 1989). Because of clear definitions of functionality and the specification of uncoupled interfaces, a modular architecture enables such a black box approach to component development.

Modular product architectures also allow production lead times to be reduced in a high-variety make-to-order environment because, as discussed in the section on product variety, diverse products can be assembled from a set of standard components. Because assembly is frequently a much shorter production step than the fabrication or procurement of individual components, lead times can be short under these assemble-to-order conditions. This advantage to the modular architecture persists even when the components of a product with an integral architecture are produced with flexible process technology.

5.4 Product Change

The architecture of the product is linked to the ability to change the product, both within the lifetime of a particular artifact and over the life cycle of several generations of product. The ability to change the product is closely related to the ability to offer product variety discussed in section 4. Within the lifetime of a particular artifact, change may be desirable in order to replace worn or consumed parts (as in razor blades, vacuum cleaner bags, or film) or to upgrade product performance (as in higher-capacity memory chips for a computer). Because desired change is typically associated with a particular functional element of the product, a modular architecture facilitates this change by allowing a functional element to be modified by changing one component, without replacing other, still adequate, components of the product.

The same principle applies to change over the life cycle of several generations of product. Because change across generations of products is frequently associated with changing the capability of a product relative to one or more functional elements, a modular architecture allows the impact of change to be localized to a few components. The desire for continual product change motivates the use of a modular architecture for at least the most dynamic elements of the product. For example, the Sony Walkman architecture allows the tape transport mechanism to be reused in many successive models while the enclosure parts can be easily changed for each model (Sanderson and Uzumeri 1992). *Virtual design* is a term Sanderson and Uzumeri use for this superposition of several product cycles involving changes to only a few components onto the longer life cycle of a technological platform. This virtual design is enabled by a modular product architecture. Sanchez and Sudharashan (1992) argue that a modular architecture is one of the enabling elements of *real-time market research,* the extremely rapid development and trial introduction of incrementally changed products. Cusumano and Nobeoka (1992), in summarizing several previous studies of the world automobile industry, identify *project scope*— the percentage of unique components a manufacturer designs from scratch in house— as a key variable relating to product development performance. The architecture of the product, and the degree of modularity in particular, dictate how difficult achieving a particular level of project scope will be. In software engineering, routine maintenance and generational change are notoriously difficult; Korson and Vaishnavi (1986) find strong empirical evidence that modular software architectures facilitate program change.

5.5 Organization of the Firm

Highly modular designs allow firms to divide their development and production organizations into specialized groups with a narrow focus. This organizational structure may also extend to the supplier network of the firm. If the function of a component can be precisely specified and the interface between the component and the rest of the product is fully characterized, then the design and production of that component can be assigned to a separate entity. Such specialization may have benefits for developing component quality and technological expertise.

The architecture of the product may be linked to the skills of an organization as well. Modular architectures may require better systems engineering and planning skills, while integral architectures may require better coordination skills.

One potential negative implication of a modular product architecture is the risk of creating organizational barriers to architectural innovation. This problem has been identified by Henderson and Clark (1990) in the photolithography industry and may in fact be of concern in many other industries as well. The linkages between product architecture and the organization of the firm is closely related to the notion of market and design hierarchies introduced by Clark (Clark 1985) and the idea of development task partitioning described by von Hippel (von Hippel 1990).

6. Closing Remarks

The major theme of the paper is that manufacturing firm performance is linked not only to the activities within the factory walls, but to basic product design attributes. One important attribute of the product design is the product architecture. Product architecture consists of: (1) the arrangement of functional elements, or the *function structure*; (2) the mapping from functional elements to physical components; and (3) the specification of the interfaces between interacting components. Table 1 summarizes the key ideas in the paper.

6.2 Research Directions

The research described in this paper is conceptual and foundational. My approach has been to synthesize fragments from several different disciplines, including software engineering, design theory, operations management, and product development management. I have tried to create a coherent definition of product architecture and to use logical arguments and examples to illuminate the linkages between product architecture and important issues facing manufacturing firms. I hope to have motivated a set of problems and issues, but much analytical and empirical work remains. Three research directions seem particularly interesting and important.

First, the need to make decisions involving trade-offs motivates the development of decision support models. A single model of most of the trade-offs associated with the choice of a product architecture is unlikely, and even if it were developed would probably be too complex to be useful. However, focused problems can probably be usefully isolated, analyzed, and modeled. For example, a model integrating marketing science ideas (such as those in [Green and Krieger 1985]) and production cost models could be used to evaluate the optimal variety that should be produced for each of two product architectures, integral and modular. The integral and modular architectures would each have their own cost structure and would likely lead to different levels of optimal product variety. Such a model could be used to coordinate systems engineering decisions, involving product architecture, with market segment information and production cost information. Similar models could be built to support decisions involving component standardization, investments in production process flexibility, and order lead time.

Second, I believe that a tremendous amount of insight would be gained by conducting an empirical study of the elements of difference in product architectures among the products manufactured by different firms. Such a study might lead to an identification of factors that dominate the choice of a product architecture. The results might also lead to an identification of multiple, equally effective, strategies involving different combinations of product architectures, organizational structures, and production systems. I have used a methodology I call *product archaeology*, meaning the study of the physical artifact itself, to better understand design-for-manufacturing decision making (Pearson and Ulrich 1992). This approach could also be applied to understanding the differences in product architectures among products from different manufacturers.

Finally, there is some evidence that the organization of the firm and the architecture of the product are interrelated. This linkage seems worthy of further research. Several specific questions could be addressed. Does the existence of a strong component supplier industry drive firms to organize in a particular way and to adopt a particular architecture? Do vertically integrated firms adopt more or less modular designs than firms working with outside suppliers? Does firm size or geographic location relate to the architecture of the product they manufacture? Are firms able to change the architecture of their products without changing their organizational structure? If so, which organizational structures allow the most flexibility in product architecture.

Table 1: Summary of Key Ideas.

	Integral	Modular-Slot	Modular-Bus	Modular-Sectional
Definition	• Complex mapping from functional elements to components. • And/or the component interfaces are coupled.	• One-to-one mapping between functional elements and components. • Interfaces between components are not coupled.		
		• Component interfaces are all different.	• Component interfaces are all the same.	
			• A single component (the bus) links the other components.	
Examples	Automobile unit body.	Truck body and frame.		
	Neon sign/lighting.	Table lamp with bulb and shade.	Track lighting.	
			Shelves with brackets and rails.	Stackable shelving units.
	Boom Box (some internal components are modular-slot).	Consumer component stereo.	Professional audio equipment in 19 inch rack.	
	Cargo ship (hull in particular).	Tractor-trailer.		Freight train.
Product Variety	• Variety not feasible without flexible component production processes.	• Products can be assembled in a combinatorial fashion from a relatively small set of component building blocks to create variety. • Variety possible even without flexible component production processes.		
		• Variety confined to the choices of components within a pre-defined overall product structure.		• Variety in overall structure of the product possible (e.g. Lego blocks, piping).
Product Performance	• May exhibit higher performance for holistic functional elements like drag, noise, and aesthetics.	• Decoupling interfaces may require additional mass and space. • One-to-one mapping of functional elements to components prevents *function sharing*— the simultaneous implementation of more than one functional element by a single component— potentially resulting in physical redundancy.		
			• Standardized interfaces may result in additional redundancy and physical "overhead."	
Component Standardization		• Components can be standardized across a product line. • Firms can use standard components provided by suppliers. • Interfaces may adhere to an industry standard.		
Design and Production Lead Time	• Requires tight coordination of design tasks.	• Design tasks can be cleanly separated, thus allowing the tasks to be completed in parallel. • Components can be produced and held in inventory, allowing rapid assembly in response to an order.		
Product Change		• Functional changes can be made to a product in the field. • Manufacturers can change the function of subsequent model generations by changing a single component.		
Organization of the Firm	• Requires tight coordination of tasks.	• Specialization and division of labor possible. • Architectural innovation may be difficult. • Requires the top-down creation of a global product architecture.		

6.3 Conclusions

While the concept of an explicit product architecture is prevalent in large electronic systems design and in software engineering, to my knowledge relatively few manufacturers of mechanical and electromechanical products explicitly consider the architecture of the product and its impact on the overall manufacturing system. Hopefully, the ideas in this paper will be useful, first, by raising the awareness of the far-reaching implications of the architecture of the product, and second, by creating a vocabulary for discussing and addressing the decisions and issues that are linked to product architecture.

In addition to providing a conceptual framework, I hope that by enumerating and discussing specific trade-offs the paper contributes directly to the decisions made during the concept development and systems engineering phases of product development. These decisions include: Which variants of the product will be offered in the marketplace? How will the product be decomposed into components and subsystems? How will development tasks be allocated to internal teams and suppliers? What combination of process flexibility and modular product architecture will be used to achieve the desired product variety?

In the 1980s much attention was focused on the relationship between product design and manufacturing. While in many cases this attention led to improvements in production costs, it was focused on designing products to be easy to assemble and on reducing the cost of individual piece parts. The linkages between the product and the performance of the manufacturing firm are in fact much more extensive and include the relationship between the architecture of the product and the variety offered in the marketplace, the flexibility of the production system, the performance of the product, component standardization, the lead time required to design and build the product, the ability to change the product, and the organizational structure of the firm.

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