Holistic Customer Requirements and the Design-Select Decision

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When confronted with the task of developing a new product, a firm chooses either to design new components, unique to the product application, or to select components from those offered in the catalogs of suppliers or from those already in use in its other products. We call this the *design-select* decision. The benefits of selecting an existing component include minimizing investment, exploiting economies of scale, and preserving organizational focus. On the other hand, designing product-specific components allows a firm to (a) maximize product performance with respect to holistic customer requirements—those requirements that arise in a complex way from most of the components of a product; (b) minimize the size and mass of a product; and (c) minimize the true variable costs of production. When these benefits exceed those from selecting existing components, firms will tend to design product-specific components. Our approach is to develop this theory by linking concepts from marketing, technological innovation, and engineering design. This theory yields four testable hypotheses. A cross-sectional analysis of 225 products finds substantial support for the theory.

(Product Design; Product Development; Customer Requirements; Make-Buy Decision)

1. Introduction

When can a firm benefit from designing product-specific components? Several observations from industrial practice motivate this question. Consider a difference between desktop personal computers and notebook computers. Although both products perform essentially the same function, are produced in similar quantities, and employ similar component technologies, notebook computers contain substantially more product-specific components than desktop computers (Wildstrom 1997). In the automobile industry, many managers have expressed the hope that automobiles become more like desktop personal computers, assembled from mostly standard components (Ealey and Mercer 1992). Yet, while progress has been made in adopting product platforms (Nobeoka and Cusumano 1997), most of the components of an automobile are designed for use in a specific model. We believe that differences in the extent to which components are designed for a specific product can be explained to a large extent by the nature of the customer requirements for the product and by the fundamental constraints of engineering design.

We focus on the development of engineered assembled goods. When confronted with the task of developing a new product, a firm chooses either to design new components, unique to the product application, or to select components from those offered in the catalogs of suppliers or from those already in use in its other products. We call this the *design-select* decision. These extremes define a continuum. Intermediate alternatives include the use of components that were designed for a previous version of a similar product and "carried over" (e.g., an engine used in successive

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generations of an automobile) and components that are relatively standard, but modified slightly for a new application (e.g., a disk drive with a new mounting hole pattern for use in a specific model of notebook computer).

The central question of this paper is when firms can benefit from designing product-specific components. We do not address *who* designs these components. The actual design work might be completed by an internal product development organization, by a consulting firm, or by a component supplier organization. When we say that a "firm designs a component," we mean more precisely that a component is designed by someone specifically for use in the firm's product.

Understanding why a firm benefits from designing product-specific components illuminates issues of competitive strategy and industrial organization. In the field of competitive strategy, much attention has been devoted to the concept of *core capabilities* (Teece et al. 1997). In manufacturing firms, one commonly cited capability is that of designing new products. But should a computer company have the same depth of component design capability as an automobile company? Should an organization designing notebook computers have the same design capability as one designing desktop computers? By understanding the conditions under which firms benefit from product-specific designs, we can understand when component design capability is important. In the fields of industrial organization and technological innovation there is a rich literature on the *make-buy* decision and on vertical integration (Armour and Teece 1980, Fine and Whitney 1996, Langlois and Robertson 1989, Masten 1984). Much of the work since the 1970s has been grounded in *transaction cost economics* and in the concept of *asset specificity*. The central element of this theory is that asset specificity gives rise to vertical integration because of the threat of opportunistic behavior on the part of at least one of a pair of interdependent firms (Williamson 1985). One of the most significant specific assets in manufacturing is product-specific component designs and the associated production tooling. A better understanding of the conditions under which product-specific designs are important informs the question of why asset specificity may exist in a particular situation, thus revealing a driver of an industrial organization variable previously treated as exogenous.

The argument of the paper can be summarized as follows: There are many benefits to selecting an existing component, including minimizing investment, exploiting economies of scale, and preserving organizational focus. On the other hand, designing product-specific components allows a firm to (a) maximize product performance with respect to holistic customer requirements—those requirements that arise in a complex way from most of the components of a product; (b) minimize the size and mass of a product; and (c) minimize the variable costs of production. When these benefits are competitively important, firms will design product-specific components. Our approach is to develop this theory by linking concepts from marketing, technological innovation, and engineering design. This theory yields four testable hypotheses. We test these hypotheses with a cross-sectional analysis of 225 products.

In the next section of the paper we develop the theory in greater detail. We describe the empirical investigation in §3 and present the results of this inquiry in §4. We discuss these results and their implications in the final section.

2. Theory

This section begins by describing the benefits of *not* designing product-specific components (i.e., of selecting existing components). We then articulate the potential benefits of designing product-specific components. Finally, we formally pose the hypotheses to be tested in our empirical analysis.

Benefits of Selecting an Existing Component

There are several potential benefits to selecting existing components when faced with the challenge of developing a new product (Fisher et al. 1999, Robertson and Ulrich 1998).

Minimizing Investment. Creating a new component requires investments in design and in production. For example, a simple component like a personal computer enclosure requires approximately $500,000 for design, prototypes, testing, and production tooling. A complex component like an automobile engine may require an investment of more than $100 million. The reuse of existing components avoids significant additional investment in product development and tooling. This argument applies directly when a firm selects a component that was designed for one of its existing or previous products, and indirectly when a firm selects a catalog item that is offered for sale by a supplier.

Scale Economies. When a component is used in more than one product, its production volume is greater than it would be for any single product. Putting aside the development and production investment issues noted above, there may be significant additional economies of scale in component production. For example, motors that have variable costs of $5.00 per unit when produced in quantities of 100,000 per year, may cost only $3.00 per unit when produced in quantities of 1,000,000 per year. A firm benefits from such scale economies whether selecting from the components used in its other products or when selecting from the stock of components sold by a supplier to multiple customers.

Organizational Focus. Facing the development of a complex product, a firm benefits from focusing on those elements of the product that will yield the greatest return. Focus leads to specialization and the development of capabilities. By selecting most components, a firm may concentrate its managerial attention on developing capabilities for "core components."

Several other motives for selecting existing components may also be present in particular situations, including: a desire for component compatibility because of network externalities (Farrell and Saloner 1985, Langlois and Robertson 1992); ownership by a supplier of unique intellectual property whose benefits may only be derived through the use of a standard component offered by that supplier; and a desire to benefit from healthy competitive forces among suppliers of standard components (Baldwin and Clark 1999, Christensen 1993, 1994, Fine 1996).

Why Design Product-Specific Components?

Given the compelling benefits of selecting existing components, how can firms benefit from designing product-specific components? Why do notebook computers contain more designed components than desktop machines? Why have automakers tried with great difficulty and limited success to use more selected components in their products?

One obvious response to the above questions is that the firm benefits from designed components when adequate existing components are not available. However, this response is basically just another way of posing the research question. A firm will not design a component when an adequate substitute already exists—hence the question of when a firm will design components is equivalent to the question of when existing components are inadequate. Two caveats bear noting. First, when a component is needed for the first time, the motive for design is not that existing components are inadequate, but rather that there are no existing components (Christensen 1994). Second, an adequate component may exist, but may be inaccessible, either because the firm is not aware of the component or because it is a proprietary part of a competitor's product. However, these are both transient cases. Once a product category is established, components will be available and a firm will design components only when these existing components are inadequate.

We argue that a firm benefits from designing product-specific components (i.e., adequate existing components will not be available) when it is competitively important to (a) maximize product performance with respect to holistic customer requirements, (b) minimize the size and mass of a product, (c) minimize the variable costs of production. This argument has three logical threads.

1. To maximize product performance with respect to holistic customer requirements, designers seek to tune many component parameters, and therefore design product-specific components.
2. To minimize size, mass, and variable cost, designers seek to minimize excess component capability, and therefore design product-specific components.
3. To minimize size, mass, and variable cost, designers adopt integral product architectures, and therefore design product-specific components.

We consider each of these elements of the theory in turn. The first point has not, to our knowledge, been previously articulated, and is a central contribution of this research, and so we treat it in more depth. The second and third points are built upon prior theoretical work described in detail in Ulrich (1995), and we therefore only summarize the associated arguments.

1. *To maximize performance with respect to holistic customer requirements, designers seek to tune many component parameters, and therefore design product-specific components.* An accepted concept in marketing is that products can be modeled as bundles of attributes, and that a customer's utility for a product can be modeled as a function of these attributes. We will use the term *customer requirements* to refer to those attributes of the product that are important to customers.

Let **P** be a vector of the product's performance on each of n customer requirements indexed by i (e.g., the acceleration, fuel economy, aesthetic quality, etc., of an automobile). Let

$$U = g(\mathbf{P}), \tag{1}$$

where U is a scalar measure of customer utility and g is a function of the product's performance. (A common marketing model is for g to be a linear weighting scheme.) For the purposes of this discussion, we assume that g represents the preferences of a single customer or of the customers of a relatively homogeneous market segment. The performance of a product with respect to a customer requirement, P_i, in turn depends on the design characteristics of the product. For physical goods, most of these design characteristics are physical (e.g., shapes, finishes, materials, etc.) and are determined in turn by the design characteristics of the *components* that comprise the product. Let

$$P_i = f_i(\mathbf{X}), \tag{2}$$

where **X** is a vector of the design characteristics of the product and f_i is the function relating these characteristics to P_i.

DEFINITION. The extent to which P_i is *holistic* is increasing in:

1. the fraction of the product's components that determines the characteristics in **X** on which P_i depends, and
2. the *complexity* of f_i;

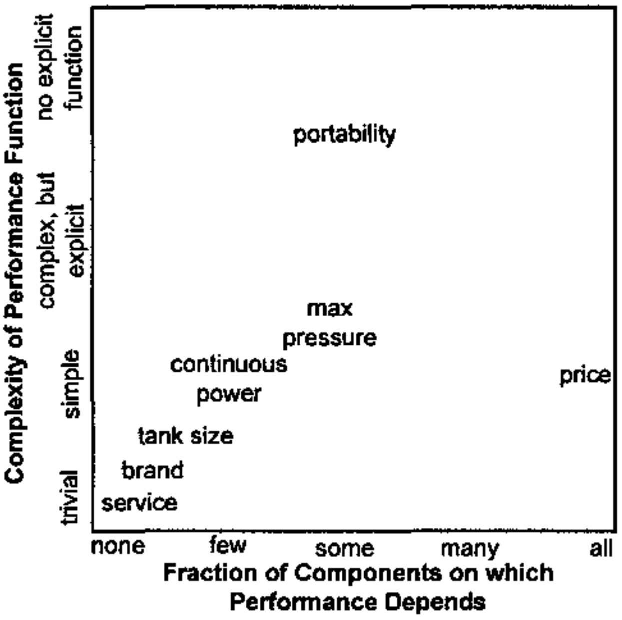
where complexity is increasing in the number of variables in f_i, in the order of f_i, and in the number of variables that are *coupled* in f_i, and where a coupled variable is an X_j in **X** for which $\partial^2 P_i / \partial X_j \partial X_k \neq 0$, for some other X_k in **X**. We further assert that if f_i cannot be expressed as an explicit mathematical function, then f_i is more complex than if there were such an explicit function.

For example, some customer requirements for portable air compressors are: price, power, tank size, maximum operating pressure, brand, portability, and availability of service. Some of the customer requirements for landing gear are: load absorption efficiency, weight, ride quality, stopping efficiency, steering quality, power consumption, and ease of maintenance. These two sets of requirements, derived from the empirical investigation to be described in §3, are plotted in Figure 1 on the two dimensions that define the degree to which a requirement is holistic. For example, price involves all of the components of the product, but for a near-commodity product like an air compressor, price is basically a function of cost, which can be determined by a simple sum of the costs of components. In contrast, portability is determined by only some of the components of the product, but there is no explicit function for computing portability. Ease of maintenance is determined by nearly all components and there is no explicit function for computing ease-of-maintenance performance. Note that, as requirements are located closer to the upper right part of the plot, they are more holistic, and that those of the landing gear are substantially more holistic than those of the air compressor.

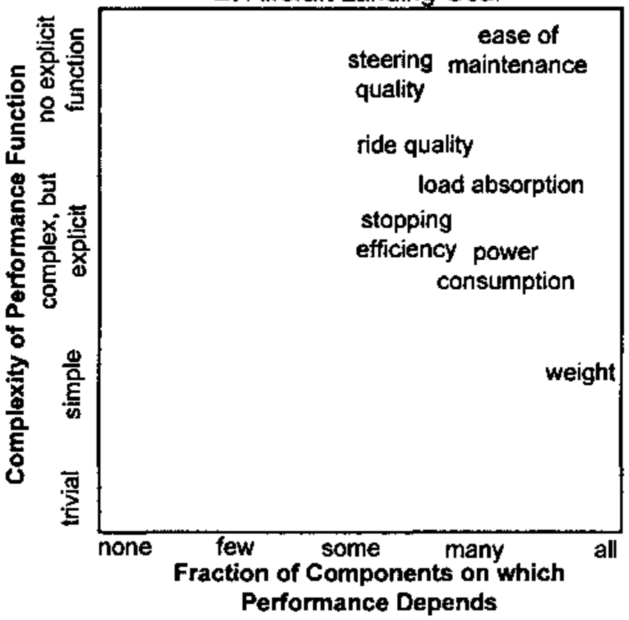
When the customer requirements for a product are holistic, overall product performance is governed by many component parameters that are related to one another in a complex interdependent fashion. As a result, performance of an individual component does not have meaning independent of the product context; the performance of a component depends on the characteristics of the other components with which it is used. Furthermore, each component will typically be characterized by many design parameters, which may need to be tuned arbitrarily in order to maximize

Figure 1 Plot of the Customer Requirements for (A) a Portable Air Compressor and (B) Aircraft Landing Gear

A. Portable Air Compressor



B. Aircraft Landing Gear



overall product performance. This leads to a situation in which a "catalog" is not feasible. There are simply too many possibly useful combinations of component design parameters to be able to enumerate them, and no matter how many existing components are available, optimal product performance will likely require some new combination of design parameters. Therefore, product-specific components must generally be designed.

For example, assume that ride quality is an extremely important customer requirement for landing gear. Ride quality is a function of most of the components of the landing gear. This ride-quality function is quite complex, and can only be partially made explicit, and only by using many coupled parameters and highly nonlinear mathematical relationships. As a result, it is not possible to decompose ride quality into independent performance requirements for each of the components. For example, there is no way to say what the ride quality of a support linkage is, without knowing what the tires and shock absorber parameters are. Furthermore, because ride quality depends on many characteristics of each landing gear component, and because designers need to have arbitrary control of each of these characteristics to achieve a competitive design, there is no possibility of creating a comprehensive catalog of landing gear components. (This isn't to say that basic design approaches are not cataloged and reused. However, each time these approaches are used the component characteristics are tuned, even if only modestly.) As a result, most of the components of a landing gear must be product specific.

Consider, in contrast, the requirement to minimize landing gear weight. Although weight depends on each and every component in the product, weight performance is a simple function (the sum) of the weights of each component. By our definition, weight is not, therefore, highly holistic. As a result, "good" components from the perspective of overall product weight performance are simply components with low weight—a measure of component quality that does not depend on the other components of the system. As a result, if weight were the only important requirement for landing gear, high performance components could be feasibly selected.

Requirements that involve highly complex functions of the product's design characteristics, but do not depend on many components, are also not holistic by our definition. If a performance requirement depends only on the characteristics of a single component, that component can be optimized in isolation and therefore used with different sets of components without modification. As a result, such components can also be selected.

2. *To minimize size, mass, and variable cost, designers seek to minimize excess component capability, and therefore design product-specific components.* Because there is a finite number of existing components, selection of an existing component is likely to result in the use of a component with excess capability or in a lowering of product performance. This is a necessary consequence of the discrete nature of the selection of existing components. For example, W.M. Berg, a supplier of components, offers three different 0.250 inch (inside diameter) ball bearings with outside diameters of 0.375, 0.500, and 0.625 inches, and associated dynamic load ratings of 37, 114, and 158 pounds. If a product requires a bearing with a dynamic load rating of 50 pounds, the smallest acceptable existing bearing (the medium-duty option) has substantial excess capability, in this case exceeding the required capacity by 128 percent. As a result, this bearing has a larger diameter than necessary, is wider than necessary, and is more massive than necessary. Therefore, to minimize mass and size, a product-specific bearing would need to be designed. This logic generalizes to most other component technologies.[1]

For similar fundamental reasons, the variable cost of producing a *given quantity* of a selected component will generally be higher than that of producing a designed component. The assertion that the variable cost of designed components can be lower than selected components may appear to be in conflict with observations of industrial practice. It is true that when a selected component is sold by a supplier to several firms, a particular firm may be able to buy this selected component less expensively than if it were to procure a designed component. However, this difference in cost is largely driven by the higher production quantities of the selected component and the associated benefits of scale economies. If we control for volume, the variable costs of production can be lower for designed components than for selected components. This is because ultimately, variable costs are largely determined by component mass and size.[2] When a product will be produced in very high volume, thereby exceeding the minimum efficient scale of component production processes, designing a component will generally result in lower variable costs than selecting a component. The variable-cost benefits of designed components will be competitively important for settings in which overall product cost is an important customer requirement and in which products are produced in very high volumes (e.g., ball-point pens, single-use razors, toys).

3. *To minimize size, mass, and variable cost, designers adopt integral product architectures, and therefore design product-specific components.* We intend *product architecture* to mean the scheme by which the function of a product is allocated to physical components of the system, and by which these components are arranged (Ulrich 1995). The basic function of a product can be decomposed into functional elements, the things a product must do to achieve its overall purpose. In *modular* architectures, the mapping from functional elements to components is one-to-one, and the interfaces between components are decoupled. In *integral* architectures, the mapping from functional elements to components is complex and/or the interfaces between components are coupled.[3]

Consider two products, a portable air compressor

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[1] Note that in addition to mass and size, these arguments extend to the consumption of energy and of time. Designed components allow energy consumption to be minimized (e.g., cellular phone power consumption), and allow the time required to perform a task to be minimized (e.g., the time required for a circuit to complete a signal processing task). However, time and energy appear to be less prevalent motives for designing components in industrial practice and they are difficult resources to measure empirically, and so we focus our argument and our associated analysis on mass and size.

[2] See Busch (1987) for models of injection molding costs based on fundamental physical phenomena. The cost drivers in these models are material mass and part dimensions.

[3] There are other related uses of the term architecture in work by Henderson and Clark (1990) and Clark (1985). von Hippel's notion of *task partitioning* (1990) is also closely related to product architec-

system and the landing gear for a commuter airplane (drawn from the data set to be described in §3). The *functional elements* of the air compressor system are: supply power, compress air, accumulate compressed air, regulate pressure, support loads, and provide carrying means.[4] The components of the compressor system are: a motor, a compressor unit, a tank, a regulator, a frame, and a handle. The compressor system embodies a modular architecture because the functional elements map one-to-one to the components.[5] The functional elements of the landing gear include: provide steering, provide braking, suspend load, and absorb landing energy. Its components include: wheels, tires, brakes, a support linkage, and shock absorbers. The landing gear is largely integral, with the suspension function, for example, mapping in a complex way to the tires, support linkages, and shock absorber components.

These architectural choices have implications for the efficient use of size and mass. The modular architecture prevents *function sharing*, the exploitation of secondary properties of one component to contribute to some otherwise unrelated function (Ulrich and Seering 1990). For example, the tank of the air compressor has secondary structural properties beyond its ability to hold pressurized air. The tank might therefore be used as part of the structural support or "frame" of the product and as part of the electrical ground circuit. This function sharing, a common property of integral architectures, conserves size and mass, but corrupts the one-to-one mapping from functional elements to components. The function-sharing tank would implement a set of functions; it holds pressurized air, but it also supports loads attached by brackets welded to its sides. As function sharing increases, component requirements become more idiosyncratic, and less likely to be fulfilled by existing components.

A similar argument applies to the *part integration* that is a common strategy in design for manufacturing and a common motive for integral product architectures (Ulrich et al. 1993, Ulrich and Eppinger 1995). Part integration, or the combination of multiple parts into one contiguous part, minimizes the use of material and space associated with component interfaces, and may improve geometric precision, but compromises the one-to-one mapping from functional elements to components. Returning to the example of the portable air compressor, perhaps the compressor handle and frame could be combined into one metal part (or the tank and handle could be combined if the function sharing strategy described above is pursued). This integration saves the size and mass associated with the interface between the handle and frame components (e.g., mounting flanges, fasteners, etc.). However, the one-to-one mapping between functional elements and components has been compromised. It is much less likely that a frame/handle component would be available as an existing component than it is that separate frame and handle components would be available. The desire for part integration in order to conserve mass and size gives rise to an integral architecture which implies that components will have to be designed.

We have made these arguments about architectural integrality in the context of minimizing size and mass. Based on exactly the same arguments made in the previous section in the discussion of variable cost and excess component capability, integral architectures and designed components also allow variable cost to be minimized.

Hypotheses

Based on the theory we have developed, we pose the following four testable hypotheses.

HYPOTHESIS 1. *The proportion of designed components in a product is increasing in the degree to which customer requirements are holistic.*

HYPOTHESIS 2. *When minimizing mass is critical to meeting customer requirements, firms will tend to design product-specific components.*

HYPOTHESIS 3. *When minimizing size is critical to*

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ture. Baldwin and Clark (1999) provide an interesting discussion of other motives for modularity.

[4] See Ulrich (1995) for a definition of functional elements.

[5] In fact, the modular architecture is so embedded in industrial practice that several of the components are named after functional elements.

meeting customer requirements, firms will tend to design product-specific components.

Hypothesis 4. *For high-volume products in markets in which product cost is critical, firms will tend to design product-specific components.*

3. Empirical Investigation

Sample

Our analysis focuses on engineered, assembled goods introduced to the market between 1992 and 1997. We gathered data using a mail survey of 1500 product development professionals. Management Roundtable Inc., a firm specializing in organizing conferences on product development management, provided us with the names of 3000 people who had attended, spoken at, or expressed interest in a conference on product development. We also purchased 5000 names from the subscriber list of *Machine Design*, a trade journal which (despite the more narrow impression of its title) is widely read by engineers involved in many types of product development. We first selected individuals with the following terms in their job titles: *engineer, product development,* or *R&D*; and *vice president, chief, director, principal, manager,* or *senior.* From these individuals we randomly selected a sample of 1500.

The survey consisted of 48 questions regarding a single product developed by the respondent. The questions were a mix of short answer, multiple choice, and Likert-scale questions. The first two questions in the survey verified that the respondent had been involved in the development of an engineered assembled product that had been introduced to the market, and that the respondent was familiar with the customer requirements, basic technology, and product design of at least one of these products. The only incentive offered for participation was a copy of a paper analyzing the results.

Of the 1500 surveys mailed, 57 were returned as undeliverable and 314 were completed and returned (22%). We consider this a relatively strong response rate for a complex survey requiring several unstructured responses and offering minimal incentives for participation. Previous surveys of product development practices conducted by consulting firms and using the Management Roundtable list have resulted in response rates of 10 to 15 percent. The set of respondents may be biased toward less busy individuals, and perhaps less pressured industries. However, such a bias should not threaten the hypothesis tests, because it would not result in a set of products that are more or less aligned with the theory. Of the 314 respondents, 41 indicated that they were either not involved in product development, were not qualified to respond, or felt that proprietary concerns precluded their participation (2 respondents). Of the remaining 273 surveys, 48 were sufficiently incomplete that they could not be used for this analysis. The final sample used in this analysis is therefore 225 products.

The products are diverse and include, for example, a pedal-powered toy car, a water cannon for movie special effects, a personal computer, and an automobile. Other examples of the products in the sample are listed in Table 1. The median product had sales of $4.9 million per year, and the 225 products collectively have annual sales of approximately $15.2 billion according to the price and volume information provided by the respondents.

Variables

Design is the dependent variable in the study. It is a measure of the degree to which components are designed for a specific product. Respondents provided estimates of the percentage of the dollar value of components in each of the following categories:

A. off-the-shelf components from the catalog of a supplier,
B. components that were relatively standard in the industry, but were customized slightly by a supplier for this application,
C. components that were designed specifically for a previous version of this product and were "carried over" to this product,
D. components that were designed specifically for this product.

We combine the percentage estimates into a single design index as follows:

$$Design = x_d + 0.75x_c + 0.25x_b \qquad (3)$$

where x_d is the percentage of components in category D, x_c is the percentage of components from category

Table 1 Examples of Products from Data Set

Consumer	**Automotive**	**Military/Aerospace**
Pedal-Powered Toy Car	All-Terrain Vehicle	Anti-Collision Light for Aircraft
Vacuum Cleaner	Tailgate Latch and Cable Assembly	Landing Gear
Rifle Scope	Back-Up Sensor	Jet Engine Fuel Pump
35 in. Television	Accessory Drive Tensioners	Single Engine Light Aircraft
String Trimmer for Lawn Care	V8 Engine	Biocular Helmet Mounted Display
Ink Jet Printer	Rack-and-Pinion Inner Tie Rod End	GPS Navigation System
Industrial	**Medical**	**Commercial**
Water Cannon for Special Effects	Infant Care Incubator	Ergonomic Work Chair
Chicken Egg Innoculator	Patient Positioning Device	Postage Meter
Portable Air Compressor	Ultrasonic Probe for Diagnostics	Desktop Personal Computer
Injection Molding Machine	Post-Op Blood Collection Device	Automated Paper Punch
Firefighter's Thermal Imaging Display	Ambulatory I.V. Pump	Office Telephone System
Nuclear Power Fuel Assembly	Disposable Difibrillation Device	Personal Digital Assistant

C, and x_b is the percentage of components from category B. These categories and weightings are somewhat similar to those in the taxonomy used by Clark and Fujimoto in their study of parts strategy and supplier involvement in the automobile industry (Clark 1989, Clark and Fujimoto 1991). We performed a sensitivity analysis to verify that our results do not depend critically on the values of these weighting factors.

Holistic is an index of the degree to which the customer requirements for the product are holistic. We asked the respondents to construct a list of five to ten "attributes that customers consider when selecting and purchasing the product." We then asked them to allocate 100 percentage points to indicate the relative importance of these attributes. For each attribute, the respondent was then instructed to assess "the approximate number of components that contribute substantially to determining the performance of the product with respect to the attribute." This assessment was done on a scale of *one or very few*, *some*, *about half*, *most*, and *all or nearly all*. Finally, for each attribute, the respondent was asked to indicate how difficult it is to predict the performance of the product with respect to the attribute, given complete knowledge of the characteristics of each of the components that make up the product. This was done on a scale of *very simple*, *simple*, *neither simple nor difficult*, *difficult*, and *very difficult*. We defined each of these options with a one-sentence description (e.g. *simple* = attribute performance can be reliably predicted through a straightforward procedure such as calculating a sum based on the characteristics of the components). We coded each of the discrete options on a 0 to 4 scale. The holistic index was then calculated as follows:

$$Holistic = \frac{1}{8} \sum_i w_i(r_i + c_i) \tag{4}$$

where w_i is the importance weight of the ith attribute as a percentage, r_i is the 0-to-4 assessment of the number of components the attribute depends on, and c_i is the 0-to-4 assessment of the difficulty of predicting attribute performance from the characteristics of the components. We normalize by a factor of 8 to provide an index with a possible range from zero to one. Note that we use "difficulty of predicting" as a substitute for functional complexity as described in §2. We do this because we felt that the concept of functional complexity was too abstract to convey in a concise written survey, and that the predictability of a function is a very close surrogate for our concept of functional complexity. In §4, we report on analysis of the sensitivity of our results to the way *Holistic* is constructed.

Mass is a measure of the importance of minimizing mass. The value of this variable is 0 for products for which the respondent does not list minimizing "mass" or "weight" as a customer requirement. For those products for which these attributes are listed, the value of *Mass* is the percentage importance weighting assigned to that requirement by the respondent.

Size is a measure of the importance of minimizing size. This variable is coded in an analogous way to *Mass*. We coded "small footprint," "small," and "small size" as equivalent customer requirements.

Cost is a measure of the importance of minimizing cost. This variable is coded using the same method as *Size* and *Mass*. We coded "cost" and "price" as equivalent customer requirements.

Log(Vol) is the base-ten logarithm of the respondent's estimate of the lifetime volume of a particular design of the product. We use a logarithmic transformation since the estimated lifetime volume ranges over eight orders of magnitude.

We also collected values for the following control variables.

Electronic is a dummy variable indicating whether or not the product is electronic. *Electronic* assumes a value of 1 given a response of 6 or 7 on a seven-level Likert scale to the statement "many of the components of this product are electronics," and assumes a value of 0 otherwise. Electronic components generally process only information and signals, and therefore require very little size and mass. Furthermore, the functions of electronic components are generally easily expressed as simple mathematical functions (addition, multiplication, logical and/or/not, etc.) The mathematical representation of electronics allows complex information processing functions (such as graphical user interfaces) to be decomposed into thousands of primitive operations such as logical operations and multiplications. As a result, collections of simple elements can be assembled to form devices with very complex functionality. Because these individual electronic components occupy very little size and mass, the size and mass penalties associated with the use of modular architectures and standard components are small relative to the overall size and mass of the devices. For this reason, electronic products are likely to use fewer designed components than products consisting substantially of nonelectronic components. (See Whitney (1996) for a thorough analysis of the differences between electronics design and the design of mechanical systems.)

Concentration is a measure of the concentration of the competition in the product category. We used a seven-level Likert scale in association with the statement "for this category of product, a few companies dominate the market." Several researchers have argued that industry concentration is an important determinant of vertical integration (MacDonald 1985, MacMillan et al. 1986, Pennings et al. 1984). A highly concentrated product market will tend to reduce the bargaining power of potential component suppliers, discouraging entry (Porter 1980). As a result, a strong component supply base may not develop, requiring product firms to design their own components. While a firm may still standardize components internally, components are likely to be less standardized than if there were a strong external supply of components.

Share is a measure of the market share of the firm selling the product. We used a seven-level Likert scale in association with the statement "for this category of product, the company has a large market share."[6] As a firm's market share increases, its production volume may become large enough relative to the entire industry that it will not incur a large scale economy penalty in using a product-specific component.

Tech Change is a measure of the rate of technological change in the industry. We used a seven-level Likert scale in association with the statement "the rate of technological change in the industry is rapid." Iansiti (1995) discusses how product development strategies are affected by market and technological turbulence. The rate of technological change may have opposing effects. For product categories in which technology is changing very rapidly, one might expect firms to be unwilling to bet on product-specific component designs, but rather to choose components from among those offered by competing suppliers (Balakrishnan and Wernerfelt 1986). However, a high rate of technological change may also induce a firm to design components because there may simply be no existing components available.

Parts is a measure of the number of parts in the bill

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[6] Two of the five respondents in the survey pre-test were unable to answer the question of what percent share the firm held in the market for the product. As a consequence, the Likert scale form was used.

of materials for the product. We intend *Parts* to capture the scope of product development and level of complexity of the product. We gave the respondents five alternatives: 1–49 parts, 50–99 parts, 100–499 parts, 500–1000 parts, and more than 1000 parts. As project scope increases, we would expect a firm to have to focus its energies on those components most critical to success, while exploiting standard components for the remainder of the product. This is somewhat analogous to the "complexity" variable used in an analysis of make-buy decisions in Harrigan (1986).

Using these variables, we estimate the parameters of the following model:

$$\begin{aligned} Design_i = {} & \beta_0 + \beta_1 Holistic_i + \beta_2 Cost_i * Log(Vol)_i \\ & + \beta_3 Size_i + \beta_4 Mass_i + \beta_5 Electronic_i \\ & + \beta_6 Concentration_i + \beta_7 Share_i \\ & + \beta_8 TechChange_i + \beta_9 Parts_i + \epsilon_i, \end{aligned} \tag{5}$$

where the variable values are those of the ith observation, the βs are constant coefficients, and ϵ_i is an error term. This model corresponds in a straightforward manner to Hypotheses 1, 2 and 3, measuring directly the impact of *Holistic*, *Mass*, and *Size* on *Design*. We test Hypothesis 4 using the variable *Cost*Log(Vol)*. We expect this variable to measure the extent to which both product cost is critical and the product is produced in high volume. We also test Hypothesis 4 with an alternate specification, substituting *Log(Vol)* for *Cost*Log(Vol)* in the model.[7] We control for the effect of electronic products in two ways. First, *Electronic* is included in our basic model of all products. In addition, we perform the analysis after excluding electronic products (i.e., those products for which *Electronic* = 1).

4. Results

Summary statistics and simple correlations among all variables are provided in Table 2 for the entire data set. Table 3 provides similar data for nonelectronic products. The simple correlations between variables provide preliminary support for Hypotheses 1, 2 and 4. The correlation coefficients between *Design* and *Holistic*, *Mass*, *Cost*Log(Vol)* and *Log(Vol)* are all significant and in the expected direction. Correlation coefficients for the nonelectronic product sample also show a significant relationship between *Size* and *Design*, providing support for Hypothesis 3. The correlation coefficients of the control variables, *Electronic*, *Concentration*, *TechChange*, and *Parts* with *Design* were significant and of the expected sign for all products. The appropriate controls were also significant for nonelectronic products.

Table 4 reports the results of ordinary least squares regressions with *Design* as the dependent variable.[8] All reported coefficients are standardized (i.e., *standardized betas*) so that the relative importance of each independent variable can be compared directly based on the magnitude of the coefficients. Model 1 tests the basic model presented in the previous section for the entire sample, while Model 2 substitutes *Log(Vol)* for *Cost*Log(Vol)*. Models 3 and 4 are applied to only nonelectronic products.

The regression analysis provides strong support for all but one of the hypotheses presented in §3. The regressions for the entire data set (Models 1 and 2) reveal coefficients for *Holistic* that are significantly different from zero. The regressions for nonelectronic products (Models 3 and 4) provide strong support for Hypotheses 2 and 4 as well, with significant coefficients for *Cost*Log(Vol)*, *Log(Vol)* and *Mass* in addition to *Holistic*. Of the hypotheses presented, only Hypothesis 2 does not receive significant support, although coefficients on *Size* are in the expected direction. This result may be due, in part, to the fact that there are very few products for which respondents listed size as an important criterion. (*Size* is not zero in 31 of 225 cases.)

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[7] We were concerned that some respondents may not have explicitly given "Cost" or "Price" as an important customer requirement because it was assumed to be too obvious. Cost was omitted by respondents in 42 of 225 cases.

[8] Note that there is an upper and lower bound on *Design*, corresponding to the cases in which either all or none of the components in a product are designed. Strictly, these bounds violate the assumptions of the OLS procedure. However, although bounded, *Design* exhibits a distribution that is essentially normal, with very little truncation. There are only 8 of 225 cases in which *Design* has a value of 1.0 and only 1 case in which it has a value of 0.

Table 2 **Summary Statistics and Correlations (Pearson) Between Variables for All Products (n = 225)**

	Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11
1. Design	0.65	0.24	1.00										
2. Holistic	0.53	0.14	0.13**	1.00									
3. Cost	19.8	17.6	0.04	0.14	1.00								
4. Log(Vol)	4.35	1.49	0.22***	−0.02	0.11*	1.00							
5. Cost*Log(Vol)	88.9	90.3	0.13**	0.13**	0.89***	0.43***	1.00						
6. Mass	1.94	5.92	0.12*	−0.06	−0.10	−0.11	−0.11	1.00					
7. Size	1.73	5.13	−0.01	−0.05	−0.09	0.09	−0.08	0.03	1.00				
8. Concentration	5.89	1.29	0.26***	0.04	−0.08	0.02	−0.06	0.03	−0.01	1.00			
9. Share	4.91	1.83	0.09	−0.05	−0.19	0.10	−0.11*	0.13**	0.06	0.28***	1.00		
10. TechChange	3.84	1.80	−0.15**	0.03	−0.22***	−0.05	−0.17***	0.03	0.07	−0.04	0.11*	1.00	
11. Parts	2.68	1.31	−0.30***	0.06	−0.05	−0.43***	−0.18***	−0.02	−0.11*	0.06	−0.01	0.16**	1.00

*$p \leq 0.10$, **$p \leq 0.05$, ***$p \leq 0.01$, two-tailed tests.

Table 3 **Summary Statistics and Correlations (Pearson) Between Variables for Nonelectronic Products (n = 153)**

	Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11
1. Design	0.73	0.18	1.00										
2. Holistic	0.54	0.14	0.25***	1.00									
3. Cost	21.2	18.4	−0.03	0.22***	1.00								
4. Log(Vol)	4.52	1.53	0.29***	0.04	0.01	1.00							
5. Cost*Log(Vol)	96.0	94.5	0.12	0.22***	0.87***	0.40***	1.00						
6. Mass	2.36	6.67	0.16**	−0.08	−0.13	−0.15*	−0.14*	1.00					
7. Size	1.33	4.72	0.14*	−0.08	−0.14*	0.20**	−0.09	−0.00	1.00				
8. Concentration	5.95	1.16	0.21***	−0.01	−0.11	0.10	−0.06	0.06	0.04	1.00			
9. Share	4.71	1.91	0.25***	−0.03	−0.24***	0.14*	−0.15*	0.19**	0.08	0.29***	1.00		
10. TechChange	3.35	1.63	0.15*	0.02	−0.20**	0.03	−0.14*	0.06	0.04	−0.06	0.12	1.00	
11. Parts	2.34	1.26	−0.21***	−0.01	0.06	−0.41***	−0.13	0.03	−0.19**	−0.00	−0.13*	0.06	1.00

*$p \leq 0.10$, **$p \leq 0.05$, ***$p \leq 0.01$, two-tailed tests.

While not the focal point of this paper, it is also interesting to note the impact of the control variables on *Design*. Most striking is the impact of electronic products on the design-select decision. In Models 1 and 2, the coefficient on the dummy variable *Electronic* is in the expected direction and highly significant ($P < 0.0001$). Moreover, *Electronic* does not simply have a fixed effect on *Design*. A comparison of Models 3 and 4 to similar regression models for electronic products shows that our theory holds well for nonelectronic products, but not for electronic products. Almost all coefficients in Models 3 and 4 are significant and the models have an adjusted R^2 of 0.209 and 0.230, respectively. In contrast, the adjusted R^2 for the electronic products are close to zero, and only the coefficient on *Concentration* is significant. Using a Chow test to compare the residual sum of squares from Model 1 (without Electronics) with the residual sum of squares from Model 3 (the nonelectronic products) and from the model for the electronic products (not shown), we can reject the hypothesis that the coefficients for electronic and nonelectronic products are equal at the 1% level ($F_{9,207} = 8.0$).

Electronic products appear to be fundamentally different than nonelectronic products with respect to the design-select decision, reinforcing the arguments of Whitney (1996). The empirical results show that electronic products use more off-the-shelf parts—in

Table 4 **Results of Regression Analysis with Design as Dependent Variable**

	All Products		Nonelectronic Products	
	1	2	3	4
Constant	0.336***	0.287***	0.293***	0.213**
	(3.77)	(2.87)	(3.09)	(2.11)
Electronic	−0.484***	−0.475***		
	(−7.42)	(−7.28)		
Holistic	0.104*	0.116**	0.239***	0.260***
	(1.90)	(2.13)	(3.21)	(3.62)
Cost*Log(Vol)	0.083		0.138*	
	(1.45)		(1.79)	
Log(Vol)		0.096		0.217***
		(1.57)		(2.68)
Size	0.031	0.020	0.113	0.074
	(0.55)	(0.36)	(1.52)	(1.01)
Mass	0.056	0.063	0.160**	0.182**
	(1.01)	(1.12)	(2.15)	(2.46)
Concentration	0.204***	0.201***	0.176**	0.156**
	(3.58)	(3.54)	(2.32)	(2.08)
Share	0.115**	0.098*	0.153*	0.117
	(1.97)	(1.66)	(1.94)	(1.51)
TechChange	0.057	0.043	0.154**	0.129*
	(0.96)	(0.72)	(2.09)	(1.78)
Parts	−0.117*	−0.093	−0.158**	−0.98
	(1.93)	(−1.44)	(−2.09)	(−1.23)
Adj. R^2	0.345	0.346	0.209	0.230
F-value	14.1***	14.2***	6.0***	6.7***
n	225	225	153	153

Standardized coefficients reported with *T*-statistics in parentheses.
$^{*}p \leq 0.10$, $^{**}p \leq 0.05$, $^{***}p \leq 0.01$, two-tailed tests.

essence, electronics technology overcomes many of the disadvantages of sharing parts across products. The constraints that electronic product designers face in terms of holistic customer requirements, mass, size, and cost are more relaxed than in the mechanical world. However, these relaxed constraints may be a double-edged sword, since barriers to entry may be lower in an environment where products can be easily constructed from off-the-shelf parts. Much recent attention has been given to "virtual" organizations and industries, in which existing components are brought together to address market needs (Langlois and Robertson 1992, Chesbrough and Teece 1996). Many of the successful virtual organizations have been in the world of electronics. This research sounds a cautionary note for those who wish to apply such lessons to nonelectronic settings. Fundamental technological constraints may govern the extent to which nonelectronic products can be developed without product-specific components.

Industry concentration also plays an important role in explaining *Design*. The coefficient on *Concentration* is positive and significant in all four models. It seems that product designers in highly concentrated industries design more product-specific parts than those in less concentrated industries. However, this result must be interpreted with caution. While we have argued that concentrated industries may have weaker component supplies than less concentrated industries, there are at least two other possible explanations. First, to some extent the need to design product-specific components may be a determinant of industry concentration. Consider a market in which the nature of customer requirements motivates the design of product-specific components. The large investment in product-specific component designs and in the capabilities to create those designs may create substantial barriers to entry, resulting in a concentrated market. This logic implies that customer requirements may cause the design of product-specific components, which in turn may cause an industry to be concentrated. To the extent that this logic is valid, *Concentration* is not an independent explanatory variable. To explore this possibility empirically, we performed regression analyses of the data omitting *Concentration* (as well as *Concentration* and *Share*). The results of these analyses were substantially the same as those reported in Table 4, except that the significance of the coefficient of *Mass* increases and the coefficient of *Cost*Log(Vol)* loses significance (for nonelectronic products). Second, there is a possible measurement bias for products supplied by firms in concentrated industries. We would expect that components would be more likely to be internally standardized (e.g. shared with the firm's other models) in these industries than externally standardized (e.g. purchased off-the-shelf). However, we did not distinguish in our survey between "carry-over" components and other internally standardized components. As a result, components that are very standard within the firm are coded the same as components that are carried over from the immediately preceding model of a product. We do not, therefore, discriminate very well the extent to which components are internally standardized.

Standard regression diagnostics and observation of the residuals reveal no significant problems with multicollinearity or heteroskedasticity. The results of the regression analysis remain essentially the same after deleting influential observations according to the guidelines provided by Belsley et al. (1980). This suggests that the outliers do not adversely affect the reported results. Our intuitive assessment of the outliers is that about half are the result of poor data due to misunderstanding of the respondent and about half are the result of unmodeled idiosyncratic factors.

We tested the sensitivity of the results to the construction of our indices for *Holistic* and *Design*. In addition to the additive formulation of *Holistic*, we considered an index constructed from the *product* of the two underlying dimensions (number of components on which the requirement depends and functional complexity). The results are qualitatively similar to those achieved with the additive index. *Design* is constructed by weighting the relative share of components designed specifically for the product, carried over from a previous product, and modified for the product by a supplier. We tested three other schemes: (1) weighing specifically designed components 100 percent, (2) weighing specifically designed components and carry-over components equally, and (3) weighing specifically designed components twice as much as carry-over components. All of these schemes produced qualitatively similar results.

Threats to Validity

The current study may not have included all contributing factors to the design-select decision. Of particular concern would be an omitted variable that is correlated with one or more of the independent variables in the regressions presented in Table 4. In this section we discuss the possible impact of three potential omitted variables: the nature of scale economies, the maturity of component markets, and firm-specific strategic choices.

Production technologies differ in the relative magnitude of fixed costs. For example, stamped metal parts require the development of relatively expensive production dies. On the other hand, machined metal parts require few fixed costs, but high variable costs. Differences in the relative importance of fixed costs may impact the design-select decision. For example, designers will prefer to select components with relatively large fixed costs, since potential benefits from a newly designed part will not outweigh the required up-front investment. In contrast, designers will tend to design components to improve holistic product performance and to reduce mass and variable cost, as long as the fixed cost penalty is not too large.

While component production technology may impact the design-select decision, it is unlikely to significantly bias our analysis. The products in our sample are all assembled products, consisting of hundreds of parts, on average. In most cases, the portfolio of technologies employed to manufacture these parts is likely to be quite varied. One exception, however, may be electronic products, where scale economies are quite important; however, we have accounted for the use of electronics directly in our analysis. Furthermore, it is unlikely that differences in the scale economies of component design and production will be correlated with the nature of customer requirements for products using these components.

Another factor in the design-select decision is the maturity of the relevant component markets. For certain new components, a competitive supply market may not exist in the short run, even if such a market will develop in the long run. The limited availability of such components may force firms to design components that they would prefer to buy from a supplier's catalog. In theory, however, the firms would have to design these components only once; in subsequent products, the component could be selected by reusing the existing part. As in the case of scale economies, ignoring the maturity of component markets would threaten the validity of the analysis only to the degree that holistic product attributes are consistently important in products utilizing new component technologies. Furthermore, we have controlled to some extent for the newness of the component market with the variable *TechChange*.

Finally, some firms may make a strategic decision to design a larger proportion of components than their competitors. For example, in computer workstations, Sun Microsystems emphasized off-the-shelf parts relative to its primary competitor, Apollo Computer (Baldwin and Clark 1999). Such strategic differences may account for unexplained variance in the proportion of components designed specifically for each product; hence omitting this strategic variable may somewhat reduce the explanatory power of the overall regression. Such strategic decisions may also be correlated with some of the independent variables in our analysis (e.g., *holistic, mass,* and *size*). For example, a firm emphasizing product-specific components may target different market segments than firms employing off-the-shelf components. Different target markets, in turn, may have significantly different customer requirements. In fact, the theory presented in §2 suggests that managers should align the design-select decision with customer requirements. As a consequence, some of the differences in strategic choices of firms may be reflected in differences in the customer requirements reported by the survey respondent.

5. Discussion

Given the economic benefits of selecting existing components, when should firms invest in designing product-specific components? We have argued theoretically and demonstrated empirically that the nature of customer requirements impacts the design-select decision. Specifically, holistic customer requirements and customer requirements involving mass and variable cost are all significant in explaining the degree to which firms design product-specific components. We also argued that the importance of small size will constrain a designer's ability to select components, but find little empirical support for this hypothesis. In addition to the specific findings presented above, this paper has highlighted the design-select decision and introduced the concept of holistic customer requirements, those customer requirements that arise from many components of the product in complex ways. We motivated the paper with a comparison of desktop personal computers and notebook computers, observing that notebook computers contain more designed components and fewer selected components than desktop computers. One explanation for this difference is that notebook computers must be small, light, and must meet holistic customer requirements like long battery life and ruggedness. Achieving these customer requirements requires components designed for a specific product. We also noted that despite substantial efforts at modularity and standardization in the auto industry, most of the components of an automobile are product-specific. We interpret this as a necessary response to a market in which holistic customer requirements and requirements involving size and mass are critically important. In the remainder of this section of the paper we discuss the relationship of these specific concepts and findings to the broader literature in management, production, and economics.

The Make-Buy Decision and Transaction Cost Economics

The design-select decision is distinct from, although related to, the classic make-buy decision. "Make" implies vertical integration of the *production* of the component. However, it is possible that a firm would "buy" a designed component (i.e., arrange with a supplier to produce a product-specific component) and/or that it would "make" a selected component (i.e., produce an industry-standard component in its own production facility). Furthermore, a designed component need not be designed internally; it may be designed by a supplier or contractor to the firm. Conversely, a selected component need not be designed by an external entity; it may have been designed internally for use in some other product. As a result, "make" is not synonymous with "design," and "buy" is not synonymous with "select."

This distinction is not made explicitly in the industrial organization literature, although it is highly related to transaction cost economics. For example, Monteverde and Teece (1982) measure the extent of "application specific engineering" as a proxy for asset specificity in order to explain Ford and General Motor's decisions to "make" or "buy" particular components for cars. However, the level of application-specific engineering is itself an endogenous decision made by the firm. More generally, the decision to design a product-specific component creates an asset in the form of production control documentation and tooling that is specific to that product. The design-select decision is in turn influenced by the nature of customer requirements. In essence, the theory presented in this paper, while consistent with the transactions cost literature in economics, makes endogenous an important element of asset specificity. More work is required to explore the linkage between the design-select decision and the make-buy decision, both theoretically and empirically.

The Impact of Changing Customer Requirements

The importance of a particular customer requirement may change over time. For example, the overall size and weight of portable computers was critical in the early days of the laptop computer industry. Recently, however, as critical components have become smaller and as the desired and available screen size has become larger, the size of portable computers has become, perhaps, a competitively less important customer requirement. As a consequence, selected components may now be more common in the laptop computer market (Wildstrom 1997). In the U.S. auto industry of the 1950s and 1960s, important customer requirements were horsepower and (large) size. In contrast, today's market values performance on dimensions such as reliability, NVH (noise, vibration and harshness), and handling. Christensen and Rosenbloom (1995) argue that evolving customer requirements in the hard disk industry resulted in significant shifts in market share across firms. Christensen also argues for a relationship between industry maturity and the motives for internal research and development efforts (Christensen 1994). Abernathy and Utterback (1978) argued that product innovations dominate the early part of the life cycle while process innovations become more important in later phases. An intriguing question is the degree to which the nature of customer requirements might evolve over the life cycle of a product in a predictable way. Thus, as the product matures, changes in customer requirements may alter the percentage of components for the product that should be designed vs. the percentage that should be selected. While a single pattern of evolution of customer requirements may not exist, there may be several common patterns that can be generalized. To answer this question will require additional data gathered within industries over time.

Holistic Customer Requirements and Organizational Structure

The paper has introduced the notion of holistic customer requirements, those that arise in a complex way from many components of a product. We expect that the nature of customer requirements will impact organizational architectures as well as product architectures (Sanchez and Mahoney 1996). In particular, we expect that more holistic customer requirements will require more integrated product development organizations. Vertical integration may not be the only way that firms attempt to achieve this integration (Mahoney 1992). For example, Clark and Fujimoto (1990, 1991) argue that an important role of the heavyweight project manager is to integrate difficult to articulate customer requirements within the detailed technical specifications of many components. Griffin and Hauser provide a comprehensive review of organizational integration mechanisms that go beyond vertical integration (1996). Iansiti and Clark (1994) provide evidence that the capability to integrate internally and externally is a factor in product success. While integrated development organizations may be important for all products, we would expect them to be particularly important for those with holistic customer requirements.

Moreover, different products, even if technologically similar, may require different approaches to product development if their customer requirements are significantly different. For example, some customer requirements for notebook computers (size, weight, and battery life) are substantially more holistic than those for desktop computers. These differences in the customer requirements across the two markets suggest that managers operating in these different markets may wish to adopt very different product development organizational structures and strategies within the same firm.

Targeting Core Capabilities

While many authors have highlighted the importance of core capabilities, few have provided guidance in targeting specific areas for capability development. The nature of customer requirements will help a firm to decide whether or not to develop significant design capabilities for components. However, the theory presented in this paper provides insight to a perhaps more important question: For *which* components should the firm cultivate design capabilities? Ideal candidates for development capabilities are components that map to multiple customer requirements in difficult-to-articulate ways. These components are likely to require significant tuning to achieve the appropriate trade-offs for the customer. As a consequence, opportunities exist for firms to develop unique capabilities in matching customer requirements to the detailed product design of these components. In addition, some components act as "glue," binding parts together, in terms of interfaces and functionality. For example, most of the components of a personal computer attach to its "motherboard" and many of a car's parts attach to the sheet metal that forms its "unibody." The capability to integrate the system efficiently and effectively may require the firm to focus on the design of these "glue-like" components.

On the other hand, components that are linked to few customer requirements in relatively straightforward ways are the best candidates for selected components. Even in situations where a firm chooses to develop these components in-house, they may be separated organizationally from the design of the product. For example, GM's Delphi component divisions are organizationally distinct from its vehicle development organization. This organizational separation helps the component divisions to seek business from non-GM customers, effectively spreading the cost of developing new components across products. The project team developing a new car may not include the group of people in charge of developing an engine that will be shared across multiple vehicles. This organizational separation may allow each group to focus on a unique set of core capabilities.[9]

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References

Abernathy, William J., James M. Utterback. 1978. Patterns of innovation in technology. *Tech. Rev.* **80**(7) 40–47.

Armour, H. O., D. J. Teece. 1980. Vertical integration and technological innovation. *Rev. Econom. Statist.* **62**(3) August 470–474.

Balakrishnan, Srinivasan, Birger Wernerfelt. 1986. Technical change, competition and vertical integration. *Strategic Management J.* 7(4) 347–359.

Baldwin, Carliss, Kim Clark. 1999. *Design Rules: The Power of Modularity.* to appear, MIT Press, Cambridge, MA.

Belsley, D., E. Kuh, R. Welsch. 1980. *Regression Diagnostics: Identifying Influential Data and Sources of Collinearity.* John Wiley & Sons, New York.

Busch, John V. 1987. Technical cost modeling of plastic fabrication processes. Doctoral Thesis, MIT Dept. of Materials Science and Engineering, Cambridge, MA.

Chesbrough, Henry W., David J. Teece. 1996. When is virtual virtuous? Organizing for innovation. *Harvard Bus. Rev.* **74**(1) 65–71.

Christensen, Clayton M. 1993. The rigid disk drive industry: A history of commercial and technological turbulence. *Bus. History Rev.* **67** 531–588.

——. 1994. Industry maturity and the vanishing rationale for industrial research and development. Harvard Business School, Working Paper 94-059.

——, Richard S. Rosenbloom. 1995. Explaining the attacker's advantage: Technological paradigms, organizational dynamics, and the value network. *Res. Policy* **24** 233–257.

Clark, Kim B. 1985. The interaction of design hierarchies and market concepts in technological evolution. *Res. Policy* **14** 235–251.

——. 1989. Project scope and project performance: The effect of parts strategy and supplier involvement on product development. *Management Sci.* **35** 1247–1263.

——, T. Fujimoto. 1990. The power of product integrity. *Harvard Bus. Rev.* **68**(6).

——, T. Fujimoto. 1991. *Product Development Performance.* Harvard Bus. School Press, Boston, MA.

Ealey, L., G. Mercer. 1992. The showroom as assembly line. *McKinsey Quart.* **3**.

Farrell, Joseph, Garth Saloner. 1985. Standardization, compatibility, and innovation, *Rand J. Econom.* **16**(1) 70–83.

Fine, Charles H., Daniel E. Whitney. 1996. Is the make-buy decision process a core competence? Working Paper, MIT Center for Technology, Policy, and Industrial Development.

——. 1996. Industry clockspeed and competency chain design: An introductory essay. Proceedings of 1996 Manufacturing and Service Operations Management Conference, Dartmouth College, Hanover, NH.

Fisher, Marshall, Kamalini Ramdas, Karl Ulrich. 1999. Component sharing in the management of product variety. *Management Sci.* **45**(3) 297–315.

Griffin, Abbie, John R. Hauser. 1996. Integrating R&D and marketing: A review and analysis of the literature. *J. Product Innovation Management,* **13** 191–215.

Harrigan, Kathryn Rudie. 1986. Matching vertical integration strategies to competitive conditions. *Strategic Management J.* 7(6) 535–555.

Henderson, Rebecca M., Kim B. Clark. 1990. Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Admin. Sci. Quart.* **35** 9–30.

Iansiti, M., K. B. Clark. 1994. Integration and dynamic capability: Evidence from product development in automobiles and mainframe computers. *Indust. Corporate Change* 3(3).

——. 1995. Shooting the rapids: Managing product development in turbulent environments. *California Management Rev.* **38** 37–58.

Langlois, R. N., P. L. Robertson. 1989. Explaining vertical integration: Lessons from the American automobile industry. *J. Econom. History* **49** 361–375.

——, P. L. Robertson. 1992. Networks and innovation in a modular system: Lessons from the microcomputer and stereo component industries. *Res. Policy* **21** 297–313.

MacDonald, James M. 1985. Market exchange or vertical integration: An empirical analysis. *Rev. Econom. Statist.* **LXVII**(2) 327–331.

MacMillan, Ian C., Donald C. Hambrick, Johannes M. Pennings. 1986. Uncertainty reduction and the threat of supplier retaliation: Two views of the backward integration decision. *Organ. Stud.* 7(3) 263–278.

Mahoney, Joseph T. 1992. The choice of organizational form: Vertical financial ownership versus other methods of vertical integration. *Strategic Management J.* **13** 559–584.

Masten, Scott E. 1984. The organization of production: Evidence from the aerospace industry. *J. Law and Econom.* **27** 403–417.

Monteverde, Kirk, David J. Teece. 1982. Supplier switching costs and vertical integration in the automobile industry. *Bell J. Econom.* **13** 206–213.

Nobeoka, K., M. A. Cusumano. 1997. Multiproject strategy and sales growth: The benefits of rapid design transfer in new product development. *Strategic Management J.* **18**(3) 169–186.

Pennings, Johannes M., Donald C. Hambrick, Ian C. MacMillan. 1984. Interorganizational dependence and forward integration. *Organ. Stud.* 5(4) 307–326.

Porter, Michael. 1980. *Competitive Strategy: Techniques for Analyzing Industries and Competitors*. The Free Press, New York.

Robertson, D., K. Ulrich. 1998. Planning for product platforms. *Sloan Management Rev.* **39**(4) 19–32.

Sanchez, Ron, Joseph T. Mahoney. 1996. Modularity, flexibility, and knowledge management in product and organization design. *Strategic Management J.* 17 63–76.

Srinivasan, V., William S. Lovejoy, David Beach. 1997. Integrated product design for marketability and manufacturing. *J. Marketing Res.* **24** 154–163.

Teece, David J., Gary Pisano, Amy Shuen. 1997. Dynamic capabilities and strategic management. *Strategic Management J.* **18**(7) 509–533.

Ulrich, Karl T., Warren P. Seering. 1990. Function sharing in mechanical design. *Design Stud.* **11**(4) 223–234.

——, D. Sartorius, S. Pearson, M. Jakiela. 1993. Including the value of time in design-for-manufacturing decision making. *Management Sci.* **39**(4) 429–447.

——, S. D. Eppinger. 1995. *Product Design and Development.* McGraw-Hill, New York.

——. 1995. The role of product architecture in the manufacturing firm. *Res. Policy* **24** 419–440.

von Hippel, Eric. 1990. Task partitioning: An innovation process variable. *Res. Policy* **19** 407–418.

Whitney, Daniel E. 1996. Why mechanical design cannot be like VLSI design. *Res. Enginr. Design* **8** 125–138.

Wildstrom, Stephen H. 1997. Eureka! Laptops that share parts, *Business Week* **July 14.**

Williamson, Oliver E. 1985. *The Economic Institutions of Capitalism*, The Free Press, New York.

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