Sourcing By Design: Product Complexity and the Supply Chain

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This paper focuses on the connection between product complexity and vertical integration using original empirical evidence from the auto industry. A rich literature has addressed the choice between internal production and external sourcing of components in the auto industry. More recent literature has developed the concept of product architecture as another choice variable that may be one of the important contributors to product complexity. In this paper, we connect these two important decisions and study them jointly. We use the property rights approach to argue that complexity in product design and vertical integration of production are complements: that in-house production is more attractive when product complexity is high, as firms seek to capture the benefits of their investment in the skills needed to coordinate development of complex designs. We test this hypothesis with a simultaneous equations model applied to data from the luxury-performance segment of the auto industry. We find a significant and positive relationship between product complexity and vertical integration. This has implications for optimal incentive structures within firms, as well as for interpreting firm performance.
(*Product Development; Product Complexity; Product Architecture; Property Rights; Transaction Costs; Vertical Integration; Automotive Industry; Supply Chain Management*)

1. Introduction

This paper focuses on the connection between product complexity and vertical integration using original empirical evidence from the auto industry. Product complexity has three main elements: (1) the number of product components to specify and produce, (2) the extent of interactions to manage between these components (parts coupling), and (3) the degree of product novelty. Variations in product complexity are driven by a number of factors such as choices in performance, technology, and product architecture. The effect of this product design choice on the outsourcing decision can be profound, as greater product complexity gives rise to coordination challenges during product development. We use the property rights approach to argue that complexity in product design and vertical integration of production are complements: that in-house production is more attractive when product complexity is high, as firms seek to capture the benefits of their investment in the skills needed to coordinate development and production of complex designs. We test this hypothesis with a simultaneous equations model applied to original data from the luxury-performance segment of the auto industry.

This research builds on efforts to capture the role of asset specificity in the vertical integration decision. Product complexity creates a variety of trans-

0025-1909/01/4701/0189$5.00
1526-5501 electronic ISSN

action costs, such as the coordination cost to design and execute production.[1] Consider the following three examples taken from our work in the auto industry.

1. Number of Components. Vehicles can be designed for electronic control with one to several multiplexing switches. Adding more multiplexes, such as modules in the doors and body, simplifies wiring, which saves space, reduces weight, and improves electrical performance. However, each additional multiplex requires its own part drawing, part number, complicated electronic testing and validation, and associated tracking and design work. Thus, adding more parts adds to the coordination needed to ensure vehicle development.

2. Component Interactions. Vehicles are often designed with front-wheel drive to provide better handling on slippery roads. However, a front-wheel-drive automatic transmission must be much narrower than a rear-wheel-drive transmission to fit between the front wheels. This narrow design requires much tighter physical adjacency of components within the transmission system. As a result, making changes to a component is much more likely to require further parts changes, as the components are tightly coupled. This requires that any part changes must be further coordinated with the designs of all the coupled parts. Thus, the more interconnected are the parts in a system, the more difficult it is to coordinate development.

3. Product Novelty. When a product involves a new architecture or new technologies, there is not a stable, well-understood set of interactions between components. The process of identifying and understanding these relationships adds to the difficulty of coordinating development. For example, in the design of the vehicle suspension system, occasionally a new configuration will be used for either the front- or rear-suspension design. When such a new type of suspension is utilized, it affects the entire vehicle's dynamics. Lengthy and difficult development iterations are required to create the desired vehicle performance. New interactions between components may be discovered and must be explored to optimize the new suspension. However, once a particular front- and rear-suspension system has been developed and used in a vehicle, the process of coordinating development for another vehicle with the same type of suspension is much easier.

In light of the costs associated with product complexity, both transaction cost theory and the property rights approach offer similar predictions, namely, that product complexity and vertical integration are complements. Transaction cost theory suggests that a firm seeking to minimize the coordination costs associated with developing a complex system will internalize production.[2] As formalized by Grossman and Hart (1986), the property rights view is that only physical asset ownership affects the incentives of the parties to invest in the skills required for coordination of complex designs. Vertical integration of production provides the manufacturer with residual rights of control over those assets, and allows the manufacturer to capture the benefits of its investment. The manufacturer will integrate production of complex systems to capture the benefits of its skill investment.

For the purposes of empirical testing, we adopt a model based on the property rights framework for the following reason: The investment in skills needed to coordinate the product development process takes place during the design phase of product development, but the benefits of this investment are determined during the production stage. That is, most auto components first are designed, then prototypes are produced and tested, after which any necessary changes are made to the initial design. It is not possible before testing to enumerate the exact amount and nature of changes in design that will be required, thus product development in the auto industry is a classic example of contractual incompleteness. After testing, the party that owns the assets at the production stage determines the changes that are to be made to the initial design. This is why we use a framework that connects skill investment to asset ownership.

[1] We refer to product complexity as a proxy for transaction costs. However, product complexity is neither limited to asset specificity nor does it necessarily capture asset specificity in entirety, as asset specificity is a very abstract concept. We use the more concrete assumptions of the property rights literature in testing our hypothesis.

[2] In Williamson's (1979) view, for example, vertical integration allows bargaining issues to be resolved by fiat; he assumes that employees (in contrast to suppliers) obey orders. Thus, coordination within the firm will be better than coordination between firms.

The usual empirical model of firm structure takes asset specificity as exogenous, focusing on firm structure as determined by specificity. Our empirical analysis explicitly accounts for the fact that product complexity and firm structure are interrelated decisions.[3] Our data set includes not only the two simultaneous choices of vertical integration (in-house production) and product complexity, but also exogenous variables, which should affect only one of the two choices directly.

The standard models also focus on component-level analysis of vertical integration in the auto industry. Our unit of analysis is the automotive system, which we believe has greater explanatory power. Complexity is a property of the development tasks that can arise as a result of the number of elements, the coupling of those elements, and the novelty of the product. This depends on the complexity of the individual component, as well as on the interrelation of components within the system. The sourcing decision, then, requires careful evaluation of the trade-offs associated with the system as a whole, as well as the part-by-part decision. Our analysis highlights how the relationship between product complexity and vertical integration might affect the conclusions that can be drawn from earlier studies and allows for better understanding of the interaction between these decisions.

Our main result is evidence of complementarity between product complexity and vertical integration. This is objectively measured and can be applied to other complex manufactured products. This finding has important implications for interpreting firm performance. We examine evidence of clustering within the auto industry around high-performance combinations.

The remainder of this paper is divided into six sections. We review the current literature in § 2. We then describe our methods in § 3. Section 4 contains the statistical evidence linking choices about vertical integration to product complexity. We present summary data on the auto systems analyzed in our data set. We present evidence of complementarity between product complexity and vertical integration. In § 5 we examine the variety of architecture and sourcing strategies observed in the industry with respect to system performance. The paper concludes with a discussion about the implications of these findings for practice and for further research.

[3] Our empirical approach is consistent with the theoretical view of Helper and Levine (1992) that asset specificity is jointly endogenous with firm structure.

2. Related Literature

This research builds on literature from several fields of study. Scholars in both economics and management science have addressed the make/buy decision. The importance of product architecture and complexity has been established in the systems engineering literature. We link these disparate strands of research to create a framework in which to study the joint decisions of product complexity and firm structure. We begin with a review of the economic framework posed by transaction cost theory and the property rights approach in order to motivate the issues confronting the firm in the make/buy decision. We review the existing empirical literature on make/buy and introduce product development concepts used in our alternate model of the coupling between product complexity and vertical integration.

2.1. Economic Theories of the Firm

Concepts of Transaction Costs. In economics, firm-level and interfirm activities are modeled as contracts (Jensen and Meckling 1976). According to transaction cost theory, the determinants of make versus buy are: (a) asset specificity, (b) uncertainty, (c) frequency of transactions, and (d) opportunism. The decision to make or to buy a part also depends on the cost associated with writing and monitoring a contract between the firm and an outside supplier—the costs associated with the transaction.[4] Transaction cost theory suggests three main reasons why it is difficult to write contracts.

[4] To date, the empirical testing with regard to theories of the firm in economics has been restricted to testing of transaction costs. While our modeling framework is based on the assumptions of the property rights approach (Grossman and Hart 1986) we also interpret our hypothesis using the more general assumptions of transaction cost theory in order to motivate our discussion of the existing empirical literature.

First, specifying all contingencies relevant to the agreement is costly, if not impossible. Second, negotiating the responsibilities of all parties under all possible contingencies is difficult. Third, when the transaction involves a high degree of asset specificity coupled with uncertainty and opportunism, writing and monitoring such a contract would be prohibitively expensive (Williamson 1979). This means that the parties will write incomplete contracts. That is, the contracts do not anticipate and cover all possible outcomes. Thus, the parties may have to renegotiate the agreement should an unforeseen event occur, and this can be time consuming and costly. This literature predicts integration when transaction costs are high. One kind of transaction cost which might be particularly salient is coordination cost.

Klein et al. (1978) argue that coordination problems arising from relationship-specific investments will be less severe if the transaction is internalized. The firm is distinct from a market entity in that disputes within the firm can be resolved without legal action or outside monitoring. Therefore, the firm is able to resolve unforeseen problems internally and thus is able to capture the full gains from its investment under all possible outcomes. From this notion, Klein et al. conclude that vertical integration is the likely firm structure for transactions in which asset-specific investment is important.

Measurement of Transaction Costs. As Joskow (1988) notes, the abstract nature of transaction cost theory makes empirical testing difficult. Testing requires concrete measures of asset specificity, as well as a means to test when and how specific investments become important. Comparing the relative performance of firms and markets has proven difficult. Since 1982, a number of papers have tackled the problem of empirical testing of transaction costs. Monteverde and Teece (1982) analyze a data set comprised of 133 component-sourcing decisions at Ford and General Motors in 1976. They proxy asset specificity with the number of engineering hours required to design a particular component. The dependent variable is the mode of the transaction: vertical integration (in-house component production) versus market transaction (outsourced component). They argue that investing more engineering hours increases the nonappropriability of technical knowledge, leading to profits that the firm can capture only through integration.

Masten et al. (1989) separate physical-asset specificity and human-capital specificity into two measures. They use the Monteverde and Teece (1982) measure of engineering hours for human capital and also use a measure of the extent to which components are produced using physical assets specific to the company. They find that only engineering hours have a significant effect on vertical integration, and argue that this demonstrates that human capital is more important than physical-asset specificity in influencing the decision to vertically integrate.

We believe that the use of engineering hours as a proxy for asset specificity by Monteverde and Teece (1982) and Masten et al. (1989) potentially confounds the *amount* of work required to develop a component with the *type* of work. Many hours could be spent to create a simplified design, which reduces coordination costs. Alternatively, many hours could be spent on a highly complex design to optimize product performance, resulting in designs requiring greater coordination. Therefore, engineering hours is not a direct measure of the cost of the transaction in the market. We propose that transaction costs are best represented as a function of product complexity.

In a study of strategic business units across sixteen industries, Harrigan (1986) suggests that successful firms with high product complexity had a higher degree of integration than firms with less product complexity. Our research, focusing on complexity at the system level within one industry, provides the opportunity to explore such issues in greater detail. Masten (1984), Walker and Weber (1987), and Masten et al. (1991) also address the relationship between product complexity and vertical integration, with complexity measured at the component level. Our system-level measures capture interactions that may be missed in component-level analysis.

The Property Rights Approach. The property rights view of the firm is a more formal model of vertical integration. This approach focuses on how different ownership structures affect relationship-specific investment incentives of the contracting parties. In this view, exemplified by Grossman and Hart (1986) and Hart and Moore (1990), physical-asset ownership confers residual rights of control over relationship-specific assets when contracts are incomplete. In particular, the ultimate division of profits will depend on the relative strengths of the parties when they renegotiate, not at the point of the initial contract. This implies that nonowning parties will underinvest in project-specific coordination skills, as they will not be able to capture the full benefits of their investment. This generates the result that the investing party should own relationship-specific assets.

There has not been any empirical testing of the assumptions of the property rights approach to date.[5] Whinston (1997) compares the Monteverde and Teece (1982) study with the property rights approach, and demonstrates that in order for vertical integration to be more likely with greater investment in skills, the returns to investment by the manufacturer must exceed the returns to investment by the supplier. We believe that this assumption is reasonable for the auto industry, as the auto manufacturer can gain returns to its investment in the total vehicle by bringing in outside suppliers, but an outside supplier cannot generate another vehicle to utilize its system investment as easily.

2.2. Theories of Sourcing and Design in Operations Management

The operations management literature also addresses the choice between in-house production and outsourcing of components. This trade-off is exemplified by the decision between purchasing standard parts and developing custom components in house. Standard parts—if they have clean, or well-understood, interfaces—can be outsourced more easily, but may present trade-offs in terms of performance and cost over custom parts development (Ulrich and Ellison forthcoming).

Baldwin and Clark (2000) argue that outsourcing, or selecting existing components from suppliers, may allow a company to benefit from competition among suppliers. However, we argue that it is not necessarily the case that outsourced components are always modular and thereby simpler and faster to develop than internally developed components. A part that is very complicated due to its performance requirements may take more time to develop with a supplier than within a firm due to coordination problems between the firms. Companies that emphasize rapid product development may wish to reduce the design iteration required between systems as a result of a more complex design by modifying the design itself, whether or not it is outsourced. The decision to change the part design characteristics and the choice of whether or not to outsource the part are separate, but, we argue tightly linked.

Clark and Fujimoto (1991) and Clark (1989) look at the choice between new and existing components in an empirical study of product development projects in the global auto industry. They examine the impact of "project scope"—a measure of the uniqueness of the part (vs. carryover parts) and the extent of development carried out by outside suppliers, on project performance (lead time and cost). The authors found that 67% of Japanese projects were "black-box," or developed by suppliers, as compared with 16% of U.S. vehicles. They argue that the black-box system is effective because the link between design and manufacturing is strong. They argue that the high percentage of unique parts and high supplier involvement contributes to an observed Japanese advantage in project lead time and cost. In this paper, our focus is on how complexity in product design affects production, and we do not address outsourcing of design.[6]

The concept of system interfaces used widely in the system-engineering literature (Suh 1990, Alexander 1964), provides an opportunity to enrich the measurement of coordination costs. If an outsourced component can be designed with well-defined interfaces, it may not require much coordination with suppliers during development.

Fine and Whitney (1996) argue that a critical capability in product development is the ability to write

[5] We are not empirically testing the assumptions of the property rights approach in this paper; we are testing our hypothesis that product complexity and vertical integration are complements.

[6] Ulrich and Ellison (1998) argue that splitting design and production of coupled systems should be avoided, but that both design and production of such systems could be outsourced and achieve integration.

competent specifications for components and systems and to be sure the specifications are realized. They list three distinct outsourcing motivations: development capability, manufacturing competitiveness, and product technology. The decision to outsource depends on whether the firms seek knowledge or capacity and whether the product is readily decomposable from the rest of the system. In our audio example, many companies with different information-processing capabilities but choosing the simpler architecture (separate cellular phone circuitry) are able to outsource phones effectively. Indeed, outsourcing a modular component may be an effective short-term remedy to a lack of development capacity within the firm. However, the make/buy decision also affects the future capabilities of the firm. (Fine 1998) A firm that repeatedly relies on an outside supplier to develop a system that is highly complex may not be able to maintain the skills needed to develop the system internally. Over time, the firm may lose the option to develop the system internally as these skills atrophy. The firm can become dependent on the supplier and therefore less able to share in the surplus generated by the development of the product. In our model, we address how ownership structures affect the incentive of the parties to invest in relationship-specific skills, but we do not address the long-term implications of such actions.

Our research builds upon the work of the above-mentioned authors. Several researchers and theories on the complexity of engineering design have also focused on coupling and interactions (Alexander 1964, Rechtin and Maier 1997, Suh 1999), but to the best of our knowledge no statistically significant testing of the relationship between this type of product complexity and vertical integration has been done before. The data set analyzed here provides the opportunity to explore these ideas empirically in a manner that has not been previously possible.

3. Methods

Sample. The analysis in this paper is based on a study of product architecture and sourcing in the auto industry. Our newly developed data set covers components in eight vehicles over five overlapping five-year time periods from 1980–1995. The companies in the sample—three in Japan, three in Europe, and two in the United States, account for roughly 90% of the global luxury-performance market by sales volume.

We studied luxury-performance cars, defined by *Consumer Reports* as vehicles priced above $30,000 in 1995. Our motivation for choosing the luxury-performance segment is that more expensive vehicles have a wider range of available choices of product architecture. As these are flagship vehicles, we expect that this segment allows for the most powerful and comparable test of the possibilities available to firms in both design and sourcing. A review of the data (see Table 1) indicates that there is a wide range in product complexity choices and sourcing choices, as well as in system performance. We collected data focused on the same components in a single vehicle segment in the auto industry in order to remove possible measurement problems caused by a data set which combines information from different vehicle types, such as that of Clark and Fujimoto (1991), or from different component types, such as Masten et al. (1989).

The unit of analysis is the automotive system. Within each company, for each luxury vehicle for each time period in the sample, we have collected data on seven key systems: engine, transmission, body, electrical, suspension, steering and brakes. Table 1 presents summary data on the systems, with respect to complexity, sourcing and quality.[7]

Data Collection. The data were collected through on-site interviews at all companies in the study. Over 1000 people were interviewed, including CEOs, chief engineers, project managers, and system engineers involved in development of each vehicle for each time period in the study. All participants were assured that only aggregate data would be presented, and confidentiality agreements were signed with each company.

Data were collected in several stages. First, after signing the agreement with each firm, a letter was sent requesting interviews with relevant project managers, system engineers, design engineers, purchasing managers, and manufacturing engineers for each vehicle for each time period in the study. The relevant

[7] For reasons of confidentiality, company-specific product complexity, sourcing, and quality means are not presented.

parties were identified by the corporate liaison for each company, and on-site meetings were arranged.

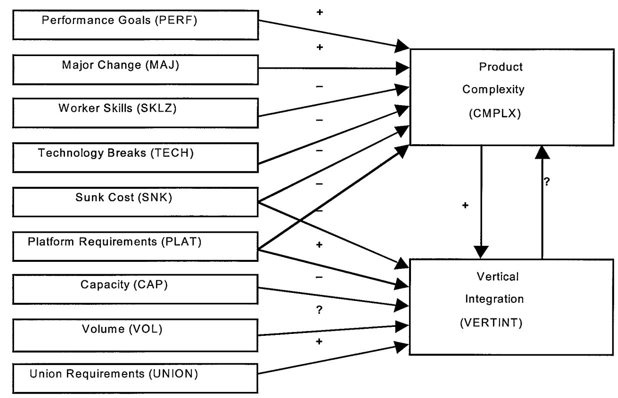
In order to ensure data accuracy, all interviewees were given an overview of the research project and definitions of key terms. All subjects were given a list of questions pertaining to the design and sourcing of components within their respective systems. The questions principally focused on objective information (e.g., number of parts in the body side) so as to minimize the likelihood of response bias. The interviews were conducted on-site at each company, ranging from three days to three months. All interviewees were given the option of being interviewed in their native languages. United States and European interviews were conducted in English and Japanese interviews were conducted in Japanese.[8]

4. Relationship Between Product Complexity and Sourcing

In this section, we begin by describing the factors that directly affect the costs and benefits of product complexity and vertical integration. Figure 1 illustrates the hypothesized relationship between these two choices.

[8] All interviews were conducted by one of the authors (S.N.). Professor Kentaro Nobeoka, a scholar with extensive experience in the Japanese auto industry, provided Japanese interview interpretation.

Figure 1 Hypothesized Relationships



The independent variables, or outside factors affecting product complexity (CMPLX), are performance goals (PERF), major change (MAJ), worker skills (SKLZ), technology breaks (TECH), sunk cost (SNK), and platform requirements (PLAT). The independent variables affecting vertical integration (VERTINT) are sunk cost (SNK), platform requirements (PLAT), plant capacity (CAP), vehicle volume (VOL), and union requirements (UNION). We define these variables and their predicted relationship to our dependent variables below. Summary statistics are presented in Table 1.

The dependent variable VERTINT is the percentage of the system produced in house, with 1

Table 1 Summary Data on Automotive Systems

System	Mean CMPLX	Std Dev CMPLX	Mean VERTINT	Std Dev VERTINT	Quality Range*
Suspension	0.35	0.26	0.50	0.30	1 to 5 (all)
Brakes	0.46	0.28	0.21	0.38	1 to 5 (all)
Transmission	0.42	0.17	0.42	0.41	1 to 4
Engine	0.47	0.25	0.48	0.25	1 to 5 (all)
Steering	0.55	0.23	0.43	0.40	1 to 5 (all)
Body	0.46	0.19	0.26	0.27	1 to 5 (all)
Electrical	0.21	0.21	0.33	0.40	1 to 5 (all)

Note. *CMPLX = product complexity, defined from 0 (low) to 1 (high) system complexity. See Appendix A for system-specific measures.
*VERTINT = vertical integration, defined as the percent of the system components produced in-house. A score of 1 indicates in-house production of system components.
*Quality is defined according to *Consumer Reports* Reliability Reviews, which are related according to vehicle system. A score of 5 = fewer than 2% problems per system (p.p.s.), the top C.R. score; 4 = 2% pps, 3 = 5% to 9.3% pps; 2 = 9.3% to 14.8% pps; 1 = more than 14.8% pps.

indicating in-house production of all components.[9] For each component, system, vehicle model, and time period, we have collected data on the make/buy decision outcome. The system measure is constructed by equally weighting the measure of each component within the system. Parts supplied to firms by wholly owned subsidiaries, such as the Delphi division of General Motors, are treated as in-house. Parts produced by partially owned suppliers, such as Nippondenso (Toyota group), were treated as outside suppliers. Sourcing spanned the entire range from 0 (outsourced) to 1 (in-house production), with a mean of 0.37 and a standard deviation of 0.36, as shown in Table 1.

The measures of product complexity used in this paper are based on detailed system design and manufacturing data. For each system, we estimate product complexity on a spectrum from 0 to 1 (no complex system interactions to high product complexity) as an unweighted average of characteristics of design complexity.[10] For some systems, measures include characteristics such as "newness"—the degree to which a design configuration has been used in the company and in the vehicle. For example, product complexity in the suspension system is calculated as an unweighted average of three (0–1) measures: newness of the design, number of moving parts in the suspension, and whether the suspension is active or passive.[11] This measure is then used for all components in the system. The dependent variable product complexity (CMPLX) measures the complexity of the system, with a score of 1 indicating high system complexity. As shown in Table 1, product complexity spanned the full range from 0 (no complex system interactions) to 0.99 (very high product complexity), with a mean of 0.42 and a standard deviation of 0.27.

[9] Masten et al. (1989) use this measure of sourcing at the component level. We believe system-level analysis captures more information about sourcing behavior. This requires weighting all components equally, as any attempt to capture value of the component requires decomposing down to the component level. We discuss the implications of this assumption for our model measurement in § 6.

[10] For each system, measures of complexity were chosen on the basis of system-engineering principles. The complexity measures used are discussed further in the appendix.

[11] These measures are discussed further in appendix.

PERF is a (0–1) measure which proxies for desired performance at the system level. Certain performance goals necessitate more complex product designs, such as more integrated architectures (Ulrich 1995). For example, a result of designing to meet high top-speed capability is a body system consisting of tightly interconnected parts.[12] In our data set, performance goals were provided by vehicle product managers, on a 0–10 scale, with 0 indicating no importance for product performance goals and 10 indicating that the vehicle competes based on high performance. We expect systems for which performance goals are very high to be associated with product complexity, and, hence, we expect a positive relationship between PERF and CMPLX.

MAJ is the dummy for vehicle design status, taking on a value of 1 if the vehicle is undergoing a major change. The timing of major changes ranges from every four years to every seven years (Clark and Fujimoto 1991). The firm has an opportunity to change product complexity in major changes, and we expect that in performance vehicles these changes should involve greater performance, and therefore greater product complexity. We expect a positive relationship between MAJ and CMPLX.

SKLZ is a dummy variable reflecting the presence of a worker skills/plant location effect. For example, a body design featuring many complex manual welds cannot be manufactured in an area where workers are not trained in advanced welding. Vehicle product managers were asked whether absence of worker skills played a role in design considerations for each system. A score of 1 indicates a yes answer, that skill limitations were a factor in system design. Thus we expect a negative relationship between SKLZ and CMPLX.

TECH, the dummy for the state of technology, takes on a value of 1 for the year in which certain innovations, such as antilock brakes and new electronics technology in suspension systems, are introduced. This variable reflects technological innovations that have enabled increased product performance deliverable via modular components and we

[12] This is due to the requirements for overall mass reduction in order to attain high top speeds.

thus expect a negative relationship between TECH and CMPLX.

PLAT is a dummy variable for platform requirements in parts, indicating (with a "1") whether the component was designed to be used by more than one vehicle. The literature on system design suggests that constraining a component or system to meet the requirements of more than one vehicle necessarily limits the performance optimization of that part relative to the vehicle in question (Ulrich 1995). For example, the Ford Taurus underbody greatly restricted design complexity on the Lincoln Continental underbody design that was built on the same platform. For this reason, we predict that PLAT will have a negative affect on CMPLX. Platform requirements could support in-house production through economies of scale achieved through parts sharing. For this reason, we hypothesize a positive relationship between PLAT and VERTINT.[13]

SNK is a dummy variable for existing sunk cost/plant investment. Managers were asked whether or not existing plant equipment directly affected their design choices for the system. Systems are often designed around investment in process equipment in the plants. This may constrain design to a more complex company-specific process or to a simpler process. Thus, we expect SNK to have a significant effect on CMPLX but make no prediction on the direction of the relationship. Managers were also asked whether or not existing plant capabilities directly affected their sourcing decision. A system may be built in-house as a result of existing plant investment. On the other hand, systems are often outsourced because of existing in-plant manufacturing problems. For this reason, we also test for the relationship between SNK and VERTINT, but we make no prediction on the direction of the relationship.

CAP is a dummy variable indicating limited plant production capacity or capability. System managers were asked if the plant had insufficient capacity to manufacture system designs in-house. If a certain system, like a one-piece body side, exceeds the capacity of current plant equipment, it may be outsourced. For this reason we predict a negative relationship between CAP and VERTINT.

VOL is the variable for vehicle volume. We calculate volume two ways, as absolute company volume, and as the percentage of the overall firm devoted to luxury-performance cars. We believe both measures can influence sourcing decisions. BMW, for example, is much smaller than Toyota in absolute volume, but Toyota's luxuxry-performance volume is much smaller than BMW's. BMW may be able to command a larger, not smaller, ordering capacity with suppliers because of its much larger luxury-performance market. Toyota may also be able to use its market dominance in other segments to source more effectively in luxury performance. For this reason we make no prediction about the direction of the relationship between VOL and VERTINT.

The dummy variable UNION takes on a value of 1 if a component is produced in-house and is covered under a union agreement. If a system is produced in a plant with a union agreement, it may be very difficult to outsource any of the components in the system because of the extreme cost and risks associated with union renegotiation. For this reason we expect a positive relationship between UNION and VERTINT.

4.1. The Statistical Model

Our principal concern in this paper is to study the relationship between product complexity and sourcing. The preceding discussion suggests that some form of integration is likely to be chosen as product complexity increases. However, we have argued that product complexity and sourcing are coupled. Econometrically, this suggests a model where product complexity and sourcing are simultaneously determined, so that our model should treat these two variables as jointly endogenous.

Hausman (1983) has shown that using an instrumental variables approach always leads to consistent estimation for an identified model; this approach is taken in this paper. To test for the relationship between product complexity and sourcing, we esti-

[13] Consistent with transaction cost theory, we assume that although suppliers may be able to enjoy the same economies of scale, they will not pass along the full savings of platform sourcing, because of the holdup problem discussed in § 2.

mate the following model:

$$\begin{aligned}\text{CMPLX} = {} & \beta_{10} + \beta_{11}\text{PERF} + \beta_{12}\text{MAJ} + \beta_{14}\text{SKLZ} \\ & + \beta_{15}\text{TECH} + \beta_{16}\text{SNK} + \beta_{17}\text{PLAT} \qquad (1) \\ & + \gamma_1\text{VERTINT} + \varepsilon_1,^{14}\end{aligned}$$

$$\begin{aligned}\text{VERTINT} = {} & \beta_{20} + \beta_{23}\text{CAP} + \beta_{26}\text{SNK} \\ & + \beta_{27}\text{VOL} + \beta_{28}\text{UNION} \qquad (2) \\ & + \beta_{29}\text{PLAT} + \gamma^2\text{CMPLX} + \varepsilon_2.^{15}\end{aligned}$$

Optimal Instrumental Variables. A consistent estimator of the system described by (2.1) and (2.2) is optimal instrumental variables, instrumenting for CMPLX in (2.2) and VERTINT in (2.1) with the instruments Z. The instruments used for Equation (2.2) are: PERF, MAJ, SKLZ, and TECH. The instruments used for Equation (2.1) are CAP, VOL, and UNION. As this system is highly coupled, we expect that there will be correlation between all of the factors affecting both decisions.[16] However, the presence of a variable in a particular equation indicates that this factor directly affects the decision to be made, rather than affecting this decision through a second-order effect (through the rest of the system). The idea behind the instrumental variables approach is that these variables are uncorrelated with stochastic disturbances in the dependent variable to be measured, but are correlated with the jointly endogenous variable.

For example, making a major change to a system such as the engine consists of changing the design of the engine, thus directly affecting its product complexity. It may be the case that this change in product complexity requires a change in the sourcing of the engine system components. This effect, however, is of second order. That is, major changes do not directly create changes in sourcing for a system; in fact, many companies prefer to use the same supply strategy even when system changes in design are made. For this reason, we expect sourcing to be indirectly affected by major change through product complexity, and we expect to see that sourcing and major change are highly correlated, but we do not expect that unobserved variation in sourcing will be correlated with major change. Similarly, we assume that performance goals, worker skills, and technology breaks affect sourcing decisions through their direct effect on product complexity, and thus are correlated with sourcing, but are uncorrelated with unexplained variation in sourcing. We assume that capacity limitations, company volume, and union are similarly uncorrelated with unexplained variations in product complexity, but are correlated with product complexity decisions.

[14] If one were to run only the Regression (2.2), using a method such as ordinary least squares (OLS), the resulting measure for β_{20} would be biased and inconsistent, because of the presence of ε_1 in the variable CMPLX. This is because there may be unobserved factors in sourcing which are correlated with the complexity decision. For this reason, we use a simultaneous equation.

[15] Plus year, company, and system dummies.

[16] Table 2 presents simple correlations of the variables.

Table 2 Correlations

	system	cmplx	perf	maj	cap	sklz	tech	snk	vol	union	plat	vertint
system	1											
cmplx	−0.07	1										
perf	0.05	0.25	1									
maj	0.01	0.29	0.15									
cap	0.27	−0.11	−0.2	0	1							
sklz	0.51	−0.06	−0.2	0	0.59	1						
tech	0.14	−0.09	0.09	0.1	0.15	0.18	1					
snk	0.19	0.02	−0.2	−0.1	0.3	0.47	−0.1	1				
vol	0.01	−0.24	−0.1	−0.2	0.15	−0.1	−0.1	0.09	1			
union	0.01	0.32	−0.2	−0.4	−0.2	−0	−0.1	0.22	0.77	1		
plat	0.35	−0.12	−0.1	−0.1	0	0.1	−0.2	0.05	0	0.17	1	
vertint	−0.17	−0.15	−0.2	−0.2	−0.2	−0.3	−0.2	0	0.74	0.55	0.06	1

Table 3 Regression Results for Product Complexity

Dependent Variable	Coefficient	Std. Error	z	$p > \|z\|$
CMPLX				
Independent Variables				
PERF	−0.46	0.66	−0.69	0.49
MAJ	1.14	0.43	*2.68	0.007
SKLZ	−0.87	0.64	−1.37	0.17
TECH	−1.08	0.51	** − 2.12	0.03
SNK	1.13	0.61	1.84	0.07
PLAT	−0.81	0.39	** − 2.1	0.04
Instrumental Variables				
CAP	0.63	0.5	−1.2	0.21
VOL	−1.27	1.46	−0.87	0.38
UNION	−0.53	0.67	−0.8	0.42

* = significant at the 0.01 level; ** = significant at the 0.05 level. $N = 134$, Adjusted $R^2 = 0.30$; $\text{Chi}^2 = 34.95$

Specification Tests. To test the effect of CMPLX on VERTINT (Equation 2.2), we estimate Equation (2.1) and formally validate our model using the Hausman Specification Test (Hausman and Wise 1978) as follows. We believe that the CMPLX decision is made as a result of performance goals, major changes, worker skills, technology breaks, and platform requirements, as well as potentially unobserved other factors, which we label "ε_1". Using instrumental variables, it is possible to estimate CMPLX directly as a function of all the instruments, generating a predicted value $\hat{c}$.[17] We first ran a probit regression of all the instruments on CMPLX to obtain $\hat{c}$. The results of this regression are presented in Table 3. The difference between the observed values CMPLX and the new values $\hat{c}$ is our estimate of ε_1, or the unobserved factors in CMPLX, which we label $\hat{v}$. We then ran an ordered probit regression of Equation (2.2), with the addition of $\hat{v}$ as a variable. If, in fact, we have removed the relationship of VERTINT on CMPLX, there should be no relationship between ε_1 and VERTINT.[18] That is, there should be no correlation between unobserved variables in CMPLX and the sourcing decision. Table 4 presents the results of the Hausman Specification Test. The relationship between $\hat{v}$ and VERTINT is not significantly different from zero, at standard levels of confidence.[19] As there is no relationship between our estimated error and VERTINT, this allows us to measure the effect of CMPLX on VERTINT using an ordered probit regression.

Table 4 Hausman Specification Test

Dependent Variable	Coefficient	Std. Error	z	$p > \|z\|$
VERTINT				
Independent Variables				
CMPLX	1.61	0.59	*2.7	0.007
SNK	−1.4	0.56	* − 2.439	0.02
VOL	−4	3.5	−1.127	0.26
UNION	4.9	2.3	*2.09	0.04
PLAT	0.64	0.3	*2.1	0.04
Error Term				
VHAT	−0.73	0.87	−0.85	0.4
System Dummy Variables				
SUSP	0.32	0.46	0.7	0.5
BRKS	−0.02	0.5	−0.05	0.96
TRANS	−0.92	0.47	** − 1.922	0.05
ENGINE	−0.25	0.49	−0.5	0.6
STEER	−0.25	0.49	−0.5	0.6
ELECTRICAL	0.11	0.53	0.22	0.82

* = significant at the 0.01 level; ** = significant at the 0.05 level. $N = 134$, Pseudo $R^2 = 0.37$

In summary, our model accounts for the econometric implications of the coupling between the complexity and sourcing decisions. Our study design permits us to measure the impact of product complexity on sourcing, and we have formally validated our approach using a test of the simultaneity between the complexity and sourcing decisions. Again, consistent with system engineering and transaction cost arguments, we predict that CMPLX will have a positive affect on VERTINT ($\gamma_2 > 0$). No predictions are made concerning company-specific effects.

4.2. The Effects of Product Complexity on Sourcing

Table 5 presents the results of an ordered probit regression of Equation (2.2). We tested for the effect of years on sourcing; we found that year dummies are not significant, and thus dropped year dummies from

[17] This is the same as running the reduced form regression $\text{CMPLX} = Z\Pi + V$. See Hausman (1983).

[18] This is the same as running $\text{VERTINT} = x\delta + \gamma_1\text{CMPLX} + \gamma_2\hat{v}$. H_0: $\gamma_2 = 0$. See Hausman (1983).

[19] This result assumes errors are normally distributed. However, with a Z statistic of -0.845, less than one, a regression with log values is unlikely to reverse the result of rejection of the null hypothesis.

Table 5 Regression Results for Sourcing

Dependent Variable	Coefficient	Std. Error	z	$p > \|z\|$
VERTINT				
CMPLX	1.61	0.59	*2.7	0.007
Independent Variables				
SNK	−1.4	0.56	* −2.439	0.02
VOL	−4	3.5	−1.127	0.26
UNION	5.1	2.4	*2.095	0.04
PLAT	0.62	0.3	*2.018	0.04
System Dummy Variables				
SUSP	0.275	0.54	0.507	0.61
BRKS	−0.01	0.57	−0.017	0.99
TRANS	−1.42	0.74	** −1.92	0.05
ENGINE	−0.14	0.61	−0.229	0.82
STEER	−0.13	0.62	−0.204	0.84
BODY	−0.08	0.53	−0.149	0.88

* = significant at the 0.01 level; ** = significant at the 0.05 level. $N = 134$, Adjusted $R^2 = 0.37$; $\text{Chi}^2 = 113.28$

our estimation.[20] Company dummies were included but are not reported for reasons of confidentiality. One company had a significant, and negative, effect on sourcing; the rest of the companies did not have a significant relationship with sourcing. System, volume, and capacity dummies did not play a significant role in the sourcing decision.

CMPLX, our measure of product complexity, has a positive and significant effect on the percentage of the component produced in-house at a 99% confidence level. This means that an increase in product complexity is correlated with an increase in in-house production. This is consistent with our prediction that investment in skills to coordinate complex designs is supported by ownership of the key assets used in production.

As predicted, UNION, which measures the extent to which union requirements influence the decision to vertically integrate, has a positive and significant impact on in-house production at a 95% confidence level. This is consistent with our interview data on the U.S. auto industry, where union agreements cover all components currently manufactured within a U.S. plant. To outsource a component, it is necessary to renegotiate the union agreement, a prospect that is costly at best, and at worst, can result in a debilitating strike. As a result, U.S. firms face a far greater penalty in attempting to outsource existing components, and are thus more likely to build even simpler systems in-house.

Platform requirements (PLAT) also affected sourcing positively at a 95% confidence level. This indicates that constraining components to serve a platform of vehicles increased the likelihood of in-house production. This result, consistent with transaction cost theory, suggests that the benefits to increased order volume made possible by producing a common component for several vehicles are better obtained through in-house production. This is because the firm would face additional monitoring costs by outsourcing, allowing suppliers to build similar economies of scale. It may also be the case that the platform requirement requires more modular designs, which affect sourcing indirectly by reducing the coordination costs associated with outsourcing.

Sunk cost (SNK) had a negative and significant effect on sourcing, supporting the argument that systems may be outsourced because of existing in-plant variation.

In summary, the predictions of our model—that CMPLX, UNION, and PLAT increase the likelihood of vertical integration and that SNK decreases the likelihood of vertical integration—are supported by our regression results.

5. Impact on Product Quality Performance

Our hypothesis, that product complexity and vertical integration are complementary, suggests a model of firm performance as a function of the interaction of these two organizational design choices. Our prediction is that both complex systems produced in-house, and simple systems outsourced, will be positively correlated with quality performance.[21] Obviously,

[20] In this test, we test the null that all year dummy coefficients are equal to zero. At $F = 0.76$, $P > F = 0.60$, so we are unable to reject the null, and thus are able to drop dummy variables.

[21] Athey and Stern (1998) point out that there may be unobserved factors in the organizational choice equations that affect the performance results. With this in mind, we do not present a formal regression.

performance is affected by a variety of other factors in addition to complexity and sourcing decisions. With this is mind, we present system observations that informally support our hypothesis.

Quality, as evaluated at the system level using *Consumer Reports* reliability data, ranged from 5, a score indicating fewer than 2% of problems reported, to a score of 1, indicating greater than 14.8% reported problems. As shown in Table 1, all five possible scores were reported for all of the systems in the study. Across all the systems, mean quality performance also fit our predictions. We define CMPLX above 0.5 as complex (below 0.5 as simple) and sourcing (VERTINT) above 0.5 in-house as in-house (below 0.5 as outsourced). Simple outsourced systems had the highest mean quality of 3.7 out of 5. Complex in-house had the next highest mean, at 3.2. Complex outsourced had a mean quality of 3.1. Simple in-house had a mean quality of 2.5.

In the suspension system, the top performer in the category, with a reliability score of 5, featured a simple outsourced design, which supports our view that simpler products can be more effectively outsourced. The worst performer in the category, with a score of 1, featured a complex outsourced design, consistent with the idea that complex designs cannot be easily decomposed and outsourced. In the body system, the best performers, with scores of 5, were complex in-house and simple outsourced. The worst performers, with scores of 1, were simple in-house and complex outsourced. Again, this is consistent with our hypothesized relationship between complexity and sourcing. The top performers in the transmission system, with scores of 4, were simple outsourced and complex outsourced. The worst performers, with scores of 2, were simple in-house. The performance of the simple outsourced and simple in-house vehicles is consistent with our predictions.

The performance of the vehicle featuring the complex transmission design with outsourced production of transmissions raises a measurement issue we encountered with our data set. The system in question was highly complex, and the company in question produced the most integral components of the system in-house, outsourcing only the simplest components. On a content basis, their in-house production was not low, and their performance can be seen as consistent with our hypothesis that complex in-house ought to perform highly. However, any attempt to correct for content requires decomposing down to the component level. We recognize that this may understate the sourcing percentage at some of the firms in our study. As this bias reduces the likelihood that we will observe the predicted relationship between architecture and sourcing, we believe such corrections would strengthen our results.

All the companies manufacture the five major engine-system components (cylinder head, engine block, crankshaft, camshaft, and intake manifold). The variation in sourcing centered around more potentially decomposable components. The top performers were complex outsourced, again, because of the equal weighting of component sourcing. The worst performer was simple in-house. In the brake system, all but one of the companies in the study outsource brakes as a complete system. The lack of variance in sourcing limits our ability to interpret quality with respect to our hypothesized relationship between architecture and sourcing. The top performers were both complex outsourced and simple outsourced. The worst performer was simple in-house. In the electrical system, the worst performer was simple in-house and the top performer was simple outsourced.

The steering system results also reflect another measurement issue we encountered in our data set. The best performer, with a score of 5, was complex outsourced. The worst performers were simple in-house and complex in-house. Past empirical studies of the auto industry have treated the relationship between Japanese manufacturers and their partially owned *keiretsu* suppliers as comparable to relationships between U.S. and European automakers and their suppliers. That is, studies like Clark and Fujimoto (1991) have treated parts developed by *keiretsu* suppliers as outsourced by the parent firms.[22] However, in the complex-outsourced steering system, as well as in many of the systems in the study,

[22] Clark and Fujimoto (1991) also treat fully owned subsidiaries such as Delphi as suppliers, where most empirical studies (Monteverde and Teece 1982, Masten et al. 1989, etc.) treat wholly owned subsidiaries as in-house.

all Japanese companies who outsourced individual parts concentrated the more complex of those parts in *keiretsu* suppliers, and outsourced simpler parts to financially separate suppliers. In contrast, most U.S. and European companies typically outsource more complex parts such as entire door systems or dash assemblies to financially separate suppliers.

The work of many researchers such as Asanuma (1989), Helper (1995), Dyer (1996), and Fujimoto (1989) indicates that the *keiretsu* relationship permits richer information exchange between Japanese manufacturers and their partially owned *keiretsu* suppliers than between financially separate firms. If greater information sharing were possible between *keiretsu* firms, then the coordination problem encountered by the firm in components development would be lower with *keiretsu* (versus non-*keiretsu*) suppliers. By component-based coordination cost, then, *keiretsu* sourcing may be closer to in-house production, and the complex-outsourced vehicle in question is closer to the complex in-house sourcing we hypothesize should be associated with greater quality. We have treated *keiretsu* firms as out-of-house with respect to the parent firms to be consistent with our system-level analysis, as well as with existing empirical methodologies. This assumption, however, also potentially understates the sourcing measure for Japanese firms in the study.

Our evidence regarding quality suggests that there is not an optimal way to configure the firm or the product, but rather that multiple optima exist. This suggests that companies should not necessarily seek to emulate the "Toyota way" of outsourcing or BMW-style product development. Rather, our research suggests that a company that optimizes over both the requirements of its product and the capability of its supply chain will outperform one which focuses only on firm structure or product characteristics.

6. Discussion and Conclusion

In summary, our model provides evidence of complementarity between product complexity and vertical integration, as well as evidence of clustering within the auto industry around high performance combinations of the two choice variables. These results strongly support the strategic importance of the product decision in the make/buy process. Given our observation that there are benefits to concentrating production of complex systems in-house and to outsourcing simpler systems, efficiency arguments suggest that profit-maximizing firms should only operate according to these approaches. This raises the question of why we ever observe firms behaving otherwise. We believe that this is a result of the chronological and organizational separation of these decisions in auto companies. Product design engineers typically determine product architecture and complexity. Purchasing agents typically make sourcing decisions. While these groups certainly interact, they do not make these decisions jointly. Our results suggest that greater coordination of these functions within the product development process could improve firm performance. Our findings also raise theoretical and empirical issues that we believe warrant further examination. We detail two issues of primary concern below.

A major simplifying assumption of this paper is that sourcing can be treated as a binary decision—either to make or to buy a part. This is done to be consistent with the simplest economic theory of vertical integration. However, actual sourcing relationships are more complex than simply make or buy. We observed other types of contracting arrangements such as *keiretsu* relationships, joint ownership agreements, equipment loans, and arms-length subsidiaries, as well as make/buy practices. These practices can create very different information structures, with potential differences in the coordination costs faced by the firm in a contracting relationship. We believe that expanding the measures of sourcing practices is an important direction for future work on make/buy.[23] In addition to the need to enrich the concept of the make/buy decision, our results also raise issues with regard to the information structure of firms.

We find that the quality benefits to designing simpler systems for outsourcing as well as the quality penalties for attempting to outsource complex

[23] Ulrich and Ellison (1998) propose some alternative sourcing measures in an empirical study of bicycle sourcing.

systems outweighed the quality benefits of in-house production of simple systems as well as in-house production of complex systems. This suggests that a complex design is still difficult to execute in-house, and that developing a simple part in-house does not necessarily improve its quality over outsourcing such a part.

In his 1988 review of empirical work in transaction cost theory, Paul Joskow raises the question: Why should information sharing among employees within a firm be better than information sharing among interested parties in a transaction? While our findings do not directly speak to this question, we believe that we have identified an appropriate framework, that of complementarity between product complexity and sourcing, through which to further explore this issue.

Acknowledgments

Support was provided by the International Motor Vehicle Program, the Center for Innovation in Product Development, the International Center for Research on the Management of Technology, and the Industrial Performance Center, all at M.I.T. Extremely valuable comments were provided by Susan Athey, David Ellison, Charles Fine, Oliver Hart, Jerry Hausman, Rebecca Henderson, Paul Joskow, and Nelson Repenning. The authors are very grateful for the cooperation of the engineers and managers at our study companies and for assistance from Takahiro Fujimoto, Johan Lilliecreutz, and Kentaro Nobeoka.

Appendix A. Product Complexity Measures

This appendix provides a brief overview of the methods used to evaluate product complexity, defined as all interactions affecting the difficulty of coordinating changes during the product development process. We first compiled a list of system-engineering principles for product development using an extensive literature survey. Chief engineers for each system at each company were also asked to list "key characteristics" most representative of product complexity, and the lists were reviewed and combined. From this list, we determined a set of questions to measure the system characteristics. Experts from all of the participating companies were asked to review the list of questions, and to add or question any item. These reviews helped to limit the potential for bias in the questions by involving a large number of experts. In some cases, as with the body, brakes, and steering systems, differences in product architecture, such as parts in the body side, mechanical vs. electrical ABS, and airbag integration, were seen to directly contribute to differences in coordination. In other systems, such as transmission, factors related to electronic interaction and coupling, such as traction control, were more significant for coordination of development. The remaining factors reflect the list that was agreed upon by the entire sample.

For each system, responses were translated into the 0–1 measure by equally weighting the answers (in most cases replies were ranked from 0–5). For example, in the suspension system, key characteristics were newness, defined as the extent to which the suspension had been used in the company; the number of moving parts in the suspension; and degree of active suspension. For newness, respondents were asked whether the suspension configuration had been used before in the study vehicle type, in other vehicle types, and if the front and rear suspension configuration had been used separately in any vehicles. Responses were scored 0 for no experience, 1 for front and rear used but not together, 2 for front and rear used in different vehicle type, 3 for front and rear suspension new. This measure was then scaled to 0, 1/3, 2/3, 1 in our data set. For moving parts, the configuration with the fewest number of moving parts, the McPherson strut system, was scored 0, the SLA system was scored 1, air McPherson was scored 2, double wishbone and delta link systems were scored 3, and rescaled similarly. The active/passive measure was scored 0 for a passive suspension, 1 for partially active, and 2 for a fully active and scaled as described above. The three measures were combined to yield a score from 0 to 1.

For the body system, key characteristics were the number of parts for the body side outer and inner, the number of sheet metal thicknesses used, the type of joints used, and the number of hits for the most complex part. For the brake system, key characteristics were the number of channels, number of solenoids, whether the system included a traction controller, and whether the ABS system was electrical or mechanical. Key characteristics for the transmission system were rear wheel vs. front wheel drive, gearsets, traction control, and automatic vs. manual. For the engine system, key characteristics were electronic control, traction control, transverse axis, and cam configuration. For the steering system, key characteristics were adjustability, knuckle attachment, and airbag integration. For the electrical system, number of multiplexes, the wiring configuration, and system integration (controls) were the key characteristics.[24]

References

Alexander, Christopher. 1964. *Notes on the Synthesis of Form*. Harvard University Press, Cambridge, MA.

Asanuma, B., 1989. Manufacturer-supplier relationships in Japan and the concept of relationship-specific skill. *J. Japanese Internat. Econom.* **3**, 1–30.

Athey, Susan, Scott Stern. 1998. An empirical framework for testing theories about complementarity in organizational design. Working paper, National Bureau of Economic Research, Inc., No. 6600, Washington, D.C.

Baldwin, Carliss, Kim B. Clark. 2000. *Design Rules: Volume I, The Power Of Modularity*, MIT Press, Cambridge, MA.

[24] Interested readers may contact the authors for more on the questions asked and the measuring scale used.

Clark, Kim B. 1989. Project scope and project performance: The effect of parts strategy and supplier involvement in product development. *Management Sci.* **35** (10) 1247–1263.

———, Takahiro Fujimoto. 1991. *Product Development Performance, Strategy, Organization, and Management in the World Auto Industry*. Harvard Business School Press, Boston, MA.

Dyer, Jeffrey H. 1996. Specialized supplier networks as a source of competitive advantage. *Strategic Management J.* **17**(4) 271–291.

Eisenhardt, Kathleen M., Behnam N. Tabrizi. 1995. Accelerating adaptive processes: Product innovation in the global computer industry. *Admin. Sci. Quart.* **40** 84–110.

Eppinger, Steven D., D. E. Whitney, R. P. Smith, D. A. Gebala. 1994. A model-based method for organizing tasks in product development. *Res. Engrg. Design* **6**(1) 1–13.

Fine, Charles. 1998. *Clockspeed: Winning Industry Control in the Age of Temporary Advantage.* Perseus Books, Reading, MA.

———, Daniel Whitney. 1996. Is the make versus buy decision a core competence? Working paper, MIT International Motor Vehicle Program, Cambridge, MA.

Fujimoto, Takahiro. 1997. The Japanese automobile supplier system: Framework, facts and reinterpretation. Working paper, Tokyo University, Tokyo, Japan.

———. 1989. Organizations for effective product development: The case of the global automotive industry. Unpublished D. B. A. dissertation, Harvard Business School, Cambridge, MA.

Grossman, S., O. Hart. 1986. The costs and benefits of ownership: A theory of vertical and lateral integration. *J. Political Econom.* **94** 691–719.

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

Hart, Oliver. 1995. *Firms, Contracts and Financial Structure*. Clarendon Press, Oxford, U.K.

———, J. Moore. 1990. Property rights and the nature of the firm. *J. Political Econom*. **98** 1119–1158.

Hausman, Jerry. 1983. Specification and estimation of simultaneous equation models. Z. Giriliches and M. Intriligator, ed. *Handbook of Econometrics*, Vol. 1, North-Holland Pub., New York, 403–426.

———, 1994. Valuation of new goods under perfect and imperfect competition. Working paper 94–121, MIT Dept. of Economics, Cambridge, MA.

———, D. Wise. 1978. A conditional probit model for qualitative choice. *Econometrica* **46**.

Helper, Susan. 1995. Supplier relations and the adoption of new technology: Results of survey research in the U.S. auto industry. Working paper, National Bureau of Economic Research, Inc., No. 5278, Washington, D.C.

———, David Levine. 1992. Long term supplier relations and product-market structure. *J. Law. Econom. Organ.* **8**(3) 561–581.

Holmstrom, B., P. Milgrom. 1994. The firm as an incentive system. *Amer. Econom. Rev.* **84** 972–991.

Jensen, M., W. Meckling. 1976. Theory of the firm: Managerial behavior, agency costs, and capital structure. *J. Financial Econom.* **3** 305–360.

Joskow, Paul. 1988. Asset specificity and the structure of vertical relationships: Empirical evidence. *J. Law, Econom. Organ.* **4** 95–117.

Klein, B., Robert G. Crawford, Armen A. Alchian. 1978. Vertical integration appropriable rents, and the competitive contracting process. *J. Law Econom.* **21** 297–336.

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

———, J. Meehan, E. Snyder. 1989. Vertical integration in the U.S. auto industry. *J. Econom. Behavior Organ.* **12** 265–273.

———,———,———. 1991. The costs of organization. *J. Econom. Behavior Organ.* **7**(1) 1–25.

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

Pimmler, Thomas, Steven D. Eppinger. 1994. Integration analysis of product decompositions. *Design Eng.* **68** 343–351.

Rechtin, Eberhardt, Mark W. Maier. 1997. *The Art of Systems Architecting*. CRC Press, Boca Raton, FL.

Simon, Herbert A. 1969. *Sciences of the Artificial*. M.I.T. Press, Cambridge, MA.

Suh, Nam. 1990. *The Principles of Design*. Oxford University Press, New York.

———. 1999. A theory of complexity, periodicity, and the design axioms. *Res. Engr. Design* **11** 116–131.

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

———, David Ellison. 1998. Beyond make-buy: Internalization and integration of design and production. Working paper, Wharton School, University of Pennsylvania, Philadelphia.

———,———. 1999. Holistic customer requirements and the design-select decision. *Management Sci.* **45** (5) 641–658.

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

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

Urban, Glen L., John R. Hauser. 1993. *Design and Marketing of New Products.* 2nd ed. Prentice Hall, Englewood Cliffs, NJ.

Walker, Gordon, David Weber. 1987. Supplier competition, uncertainty, and make or buy decisions. *Acad. Management J.* **30** (3) 589–596.

Whinston, Michael D. 1997. On the transaction cost determinants of vertical integration. Working paper, Department of Economics, Northwestern University, Evanston, IL.

Williamson, Oliver E. 1979. Transaction-cost economics: The governance of contract relations. *J. Law, Econom. Organ.* **22** 3–61.

Accepted by Karl Ulrich; received November 7, 1998. This paper was with the authors 11 months for 4 revisions.