Sourcing By Design:
Product Architecture and the Supply Chain

by

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ABSTRACT

The first paper presents a model of the supply organization problem in the automotive industry that characterizes both ownership of and access to productive assets. Contracting between a manufacturing firm and a parts supplier is modeled using an incomplete contracting framework that synthesizes those of Grossman-Hart (1986) and Rajan-Zingales (1998). Optimal assignments of ownership and access at key milestones in the product development process are analyzed with respect to their incentive effects on noncontractible investment. The merits of this approach are argued using case study evidence from an original five year study of parts contracting in the automotive industry. By incorporating quantifiable measures of design complexity from the product development literature, this model also lends itself to more refined testing of vertical integration behavior in a broad range of industries.

The second paper focuses on the coupling of product architecture and sourcing decisions using empirical evidence from the auto industry. The emphasis is on two decisions that a firm must make: whether to manufacture products in-house or to outsource - the make/buy decision, and on product complexity. There has been much research into product architecture and the make/buy decision in the auto industry, yet to the best of the authors' knowledge these decisions have never been studied jointly. The central hypothesis is that *increasing complexity in product architecture will drive vertical integration*, in that a firm seeking to minimize the coordination costs associated with developing a complex part will internalize production. This proposition is consistent with transaction cost theory regarding asset specificity. Product architectural complexity is proposed as a better proxy for asset specificity than those used previously in empirical testing of transaction costs. Original data is used to test an empirical model of the link between product architectural complexity and make/buy decisions within the context of automobile systems development. Results provide evidence of complementarity between product architectural complexity and vertical integration, as well as evidence of clustering within the auto industry around high performance combinations of the two choice variables. This has implications for optimal incentive structures within firms as well as for interpreting the performance outcomes of firms.

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I. Introduction And Overview

Two Strands of Theory

Why do firms vertically integrate or outsource? Researchers in economics and management science have been pursuing this question extensively, and largely in parallel, over the past few decades. Economists since Coase (1937) have focused on characteristics such as asset specificity and the role of physical asset ownership in affecting the investment incentives of firms. For such theories, the critical parameters which determine organizational form include the difficulty of writing contracts which specify the most relevant contingencies and the difference between the marginal returns to investment inside and outside the relationship. The abstract nature of concepts such as asset specificity has limited the testability of such models.

Management science offers many detailed examples of actual sourcing behavior by firms in a variety of industries. Wheelwright and Hayes (1984) argue, "The decision to vertically integrate often is made on the basis of information or design criteria." They argue that vertical integration can be beneficial in terms of lowering production costs, and improving control over critical parts supply, and it may be detrimental in terms of increasing production costs. Their argument is that this decision is highly specific to the industry and design in question. This focus has generated many detailed case-based accounts of actual sourcing decisions and strategies in a variety of industries, but little theory to connect them. There is clearly room for fruitful exchange across these two disciplines.

1. Bridging the Gap: Product Architecture

The theme of this thesis is that the gap between these approaches can be bridged by utilizing the link between product designs and sourcing decisions in theoretical and empirical models of firm structure. Products can be designed either as highly interconnected, complex systems which are not easily separable (e.g. fighter jet, mainframe computer), or as independent components or modules, which can be decomposed readily with standardized component interfaces (e.g. bicycle, IBM-compatible PC).[1] Ulrich (1994) defines product architecture as "the scheme by which the function of a product is allocated to physical components." A careful treatment of the concept of product architecture connects the rigorous theory of economics and the richly detailed examples of operations management, with benefits for both theory and empirical testing.

Understanding Product Architecture: Impact on Theory and Testing

Use of design complexity in the theory of the firm provides insight into the measurement of abstract concepts such as asset specificity and the role of outside options. For example, developing a highly modular design can provide the developer with skills that have high transferability, or high outside options, as these are skills focused on how to adapt a design easily to other parts. In contrast, a more integral, complex design, may require skills more specific to the part development than to any other combination of parts. Evaluating contracting over different parts with varying degrees of complexity provides an opportunity to measure how asset specificity affects contracting and negotiation. Similarly, in-house design and manufacturing capability can be interpreted in terms of its effects on bargaining power as well. For example, firms that maintain the ability to design and manufacture a product, even if they have chosen to outsource, should be more able to switch out of relations and manufacture in-house than firms that do not have such capabilities.

Purpose

The purpose of this thesis is to draw from a novel dataset based on extensive research in the auto industry to:

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[1] Nevins and Whitney (1989), Ulrich (1994).

1. Introduce concepts of product development as key parameters in the integration decision.

2. Develop and test a model of the firm in the context of actual sourcing behavior in the auto industry, including detailed measurement of asset specificity and the role of asset ownership in affecting investment incentives.

3. Provide a methodology for how to construct measures of transaction costs rooted in design complexity.

This research aims to benefit both economics and operations management by developing a more refined theory of manufacturing firms, which can be used to further study phenomena such as sourcing, product planning, and supplier relations in a variety of industries. I demonstrate how incorporating an engineering treatment of the design decision which underlies the role of the firm -- to sell products -- provides both a refinement of existing theories of the firm as well as a better empirical methodology for measuring the affect of ownership structures on firm performance.

2. Approach of the Thesis

Central Role of the Auto Industry

Both the theory of the firm and empirical studies of integration draw heavily from the automobile industry. Coase, Williamson, Hart, Rajan and Zingales all cite the General Motors-Fisher Body integration in building their models of the firm. Monteverde and Teece, in the first empirical study of the role of asset specificity on vertical integration, looked at parts sourcing in Ford and General Motors. Fine and Whitney, Eppinger, Clark and Fujimoto, Cusumano and Takeishi all draw from auto industry studies in their product development and sourcing work. I present technical evidence, rooted in the product development process, that contracting in the auto industry is well suited to the assumptions of incomplete contracting, and therefore a logical focus of a test of such theories of the firm.

3. Thesis Components - Two Essays

A. *Modeling the Supply Organization Problem*

The first of the two essays focuses on the structures fundamental to the supply organization problem in the automotive industry, characterizing both the ownership and management of productive assets. Using an incomplete contracting framework that synthesizes those of Grossman-Hart (1986) and Rajan-Zingales (1998), the essay develops a model of contracting between a manufacturing firm and a parts supplier. The model is motivated by extensive data collection at major luxury performance auto manufacturers and is motivated by case studies of actual contracting between OEMs and suppliers for parts and equipment. The key structural assumption of this model is that product architecture determines the coordination costs associated with sourcing. Within the model, I analyze the optimal assignments of ownership and access at a key milestone in the product development process, with respect to their incentive effects on noncontractible investment and information acquisition. I consider a variant of the Grossman-Hart model in which the manufacturer has an additional control variable, allowing the non-owner to have access to critical assets in product development. The implications of access to assets as an instrument forms the basis of my critique of a pure property rights approach to the auto industry. I argue the merits of the resulting theoretical synthesis using case study evidence.

The model demonstrates that asset ownership and access to assets interact in determining investment incentives of the contracting parties. This assumption is supported by case study evidence. The model demonstrates that extending the pure property rights model to include access to critical resources as well as ownership of physical assets yields predictions that are consistent with empirical evidence in the auto industry.

For operations management, the property rights approach is a new framework with which to examine the connection between product architecture and parts sourcing. For economics, the careful modeling of an applied contracting situation enriches the Grossman-Hart view by demonstrating how access to critical assets can affect investment decisions.

B. Empirical Testing of the Relationship between Complexity and Sourcing

The theoretical model of the supply problem above is simple enough to allow for a closed form solution to the auto contracting problem. However, much of the model's assumptions rest on observations in the auto industry, and not on a fully articulated theory of firm behavior. The second essay tests these assumptions in a more fully developed econometric model of the relationship between sourcing and product architectural complexity. This paper focuses on the coupling of product architecture and sourcing decisions using empirical evidence from the auto industry. The emphasis is on two decisions that a firm must make: whether to manufacture products in-house or to outsource - the make/buy decision, and on product complexity. There has been much research into product architecture and the make/buy decision in the auto industry, yet to the best of the authors' knowledge these decisions have never been studied jointly. The central hypothesis is that *increasing complexity in product architecture will drive vertical integration*, in that a firm seeking to minimize the coordination costs associated with developing a complex part will internalize production. This proposition is consistent with transaction cost theory regarding asset specificity. Product architectural complexity is proposed as a better proxy for asset specificity than those used previously in empirical testing of transaction costs. Original data is used to test an empirical model of the link between product architectural complexity and make/buy decisions within the context of automobile systems development. Results provide evidence of complementarity between product architectural complexity and vertical integration, as well as evidence of clustering within the auto industry around high performance combinations of the two choice variables. This has implications for optimal incentive structures within firms as well as for interpreting the performance outcomes of firms.

II. Ownership Structures in the Auto Industry: A Property Rights Perspective

1. Introduction

The property rights view of the firm asks how different ownership structures affect both relationship-specific investment incentives and rent seeking behavior by 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. This generates the result that the investing party should own the relationship-specific assets in order to capture more of the surplus generated by her investment. A recent strand of research by Rajan and Zingales (1998), working within the assumptions of the property rights literature, argues that access to assets can be a better mechanism for providing investment incentives than ownership. Defining access as the ability to use critical resources, both physical and human capital, the authors argue that physical asset ownership can reduce investment incentives under certain conditions where access can motivate the parties to invest more effectively.

The canonical example of contracting cited in such papers is that of General Motors and Fisher Body. Klein, Crawford and Alchian (1978) use the integration of GM and Fisher Body to argue that the move to integrate was driven by relationship-specific investments. Hart (1995) argues that ownership of Fisher Body provided GM with residual rights of control over Fisher's assets. Rajan and Zingales (1998) cite the GM-Fisher integration as a "textbook example of the disincentive created by allocating ownership to those who control investment." Such models use the same example to support seemingly opposing conclusions. The debate over the sources and effect of the GM-Fisher integration highlights a gap in the contracting literature:

The GM - Fisher Body example dates back to the 1920s. A review of modern practice in the auto industry suggests that there is much more variation in die contracting practices than is captured by current incomplete contracting models. For example, joint ownership of physical assets such as dies and stamping equipment is strictly suboptimal in the pure property rights model, yet companies such as BMW regularly loan equipment to die suppliers or jointly own equipment with suppliers. Companies like Volvo allow suppliers to develop dies on supplier-owned equipment. Similarly, under the same ownership structure, some manufacturers choose to position employees at supplier sites, gaining access to their product development, while other manufacturers do not choose to have access. There has been little study of the relative importance of ownership and access to critical resources in affecting investment incentives by the contracting parties in modern contracting arrangements.

This paper examines the interaction between physical asset ownership and access to critical resources as it affects the investment incentives of a manufacturer and supplier in development of automotive parts. A review of the auto body development process suggests that such contracting provides an ideal test of incomplete contracting models. During the normal development of an auto body, the manufacturer and suppliers contract over design and production of parts. Then, part prototypes are manufactured and assembled into a vehicle which is then crash-tested. The crash test reveals any changes which are needed in order to meet vehicle requirements. All parties involved (the auto company and its suppliers) know ex ante that 30 - 50% of the body design (and parts) will change as a result of the outcome of the crash test. However, an auto body is a highly complex design, and changes tend to reverberate. That is, a test may reveal necessary changes in one part, which can then result in necessary changes in another part, and so on. As a result, it is nearly impossible (or at least prohibitively costly) to attempt to characterize the nature and scope of these changes ex ante. Despite agreement on the total amount of change, it is never possible to specify the exact nature of changes ex ante, and therefore they cannot be written into the contract.

Using original evidence and data from a five year study of contracting over parts development in the auto industry, I develop a contracting model which maps model predictions regarding the relative importance of asset ownership and access to specific assets to empirical observations of different contracting arrangements. Building on this dataset, in Section Two I review the classic holdup problem in the auto industry, as first described by Klein, Crawford and Alchian (1978). This view assumes that physical assets in auto body contracting are all equally specific to the auto maker. In this section I present case evidence to argue that body part designs vary in complexity, as does the degree to which parts interact in the body design. I argue that the combination of these two parameters - part complexity and part interconnectedness - determines the extent to which both the knowledge required to develop the part and the equipment used to manufacture the die are specialized to the auto maker, and thus determines the holdup problem.

In Section Three, I present a model of the auto contracting problem, and, building on the pure property rights approach, incorporate measures of part complexity and interconnectedness. While the "make" or "buy" behavior in the auto industry appears to be well captured by the pure property rights model, the range of sourcing behavior in the automobile industry is much more varied. Intermediate categories of ownership and contracting, such as keiretsu, or partial ownership of suppliers, as well as equipment loans by manufacturers to supplier companies, are as common as vertical integration and complete outsourcing. In its simplest form, the pure property rights model cannot account for these intermediate categories of ownership, since partial ownership of assets - the keiretsu situation - as well as equipment loans, are strictly inferior to full ownership by one of the two parties.[2] One key aspect of such intermediate contracting arrangements appears to be the role of access to critical resources in affecting investment incentives.

In section four, I introduce a second endogenous variable, access to physical assets. Defining access, as in Rajan-Zingales (1998), as the ability to use critical resources, I posit that denying access to critical resources can be used as another instrument in

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[2] Hart, 1995, p.48

affecting investment incentives. This notion of access is simplified from Rajan-Zingales in that I only focus on investment in human capital, rather than in human and physical capital.

I argue that the prevalence of intermediate categories of ownership is a result of the interaction of the two choices, ownership of and access to physical assets, with the environment and with each other. In order to address why and how these choices interact with each other, I introduce exogenous parameters that shift the system solution. In particular, I focus on the implications that part characteristics have for skill acquisition. It seems clear that the returns to investment vary with the characteristics of the part to be sourced, yet a measure of part requirements has never been directly included as a factor in the investment decision in such models. The evidence presented in section two suggests that returns to auto part designs vary significantly in the amount of coordination that they require and that these differences in information content as well as in asset ownership account for significant differences in investment decisions under different contracting structures. One result which emerges from this analysis is that intermediate ownership structures can be optimal, including commonly observed structures such as partial ownership of suppliers or equipment loans by manufacturers to supplier companies. The contributions of the analysis are as follows:

First, this model demonstrates that optimal organizational structure can be linked to exogenous features of the economic environment. By informing the pure property rights approach with parameters reflecting part complexity and part interconnectedness, this model is able to capture the factors behind a broader range of contracting relationships which we observe empirically.

Second, I present case evidence supporting the hypothesis that investments by the manufacturer and supplier are substitutes. This result helps to explain skill investment that is seemingly wasteful ex post. I then use this result to offer an alternate explanation of the GM-Fisher body integration, as well as to explain intermediate categories of ownership in auto body contracting.

2. Automobile Manufacturing: The Holdup Problem

The basic holdup problem in body parts contracting in the auto industry, as first described by Klein, Crawford and Alchian (1978), is as follows:

The design and engineering specifications of a new automobile create value for the manufacturer. The manufacture of dies for stamping parts creates value specialized to the auto, which implies an appropriable quasi-rent in those dies. If there is a large potential cost to the manufacturer from the production delay of obtaining an alternate die supplier, this presents the opportunity for an independent die supplier to capture greater rents by demanding a higher price for die changes. Similarly, the more specific the design of the part is to the manufacturer, the fewer comparable demanders there will be for its dies. After the dies have been produced for prototype testing, the possibility for the manufacturer to negotiate a lower price for cost of changes is large. Since the likelihood of losing the quasi rents from investing in dies is large, neither party would invest skills in such an undertaking.

From this perspective, Klein, Crawford and Alchian (1978) conclude that joint ownership of physical assets, in this case the dies and stamping equipment, would resolve the holdup problem. They posit that General Motors purchased Fisher Body because although an exclusivity agreement resolved the possibility of General Motors negotiating lower part costs, contracts were unable to stop Fisher from using its bargaining power to charge higher fees. Purchase of Fisher (in house die and stamping capability) resolved the holdup problem.

This analysis focuses on physical asset specificity (specificity of the dies and the stamping press). From this perspective, it appears that dies and stamping equipment should either be jointly or wholly owned by auto manufacturers.

However, in data collection on contracting arrangements for die development in the auto industry from 1980 to 1995, I found that ownership arrangements varied widely, from supplier ownership of stamping equipment to intermediate categories of ownership such as equipment loans by manufacturers to suppliers for die development, to the vertical integration suggested by the GM-Fisher Body story. Furthermore, I found substantial variation in specificity across dies and stamping equipment.

In this paper, I take the approach of focusing on part characteristics to refine the sources of holdup faced by the contracting parties in die development. The stamping press itself is a general purpose piece of equipment. Based on extensive interviews with die suppliers and auto manufacturers, I assert that the extent to which the die is optimized to the press determines its specificity to the manufacturer. Creating a die which produces quality parts can be more or less complex depending on its design. I define part complexity using metrics based on sheet metal stamping properties.[3] Sheet metal stamping is a process of stretching or cutting metal using a die or series of dies to conform the metal to the desired shape. This process creates a strain in the material. Common problems with sheet metal stamping are tearing, wrinkling, buckling, and springback, when the sheet metal returns or "springs back" to its original shape after bending. I use these part characteristics to determine part complexity, and I posit that part complexity determines its specificity to the supplier.

Parts can also be more or less interconnected. For example, body sides can be designed in up to six parts, or as one piece. A one-piece body side is highly appealing to auto manufacturers as it requires fewer welds and provides a higher quality body. It is very difficult, however, to make a one piece body side, because there are many engineering challenges in designing the part. The body side can be divided into more easily manufacturable parts, which can be produced on standard presses, see Figure 2.2.1. However, these pieces are interconnected - changing one can necessitate corresponding changes in the other body parts.

I argue that the combination of these two parameters -- part complexity and part interconnectedness -- determines the extent to which the both the knowledge required to

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[3] See Appendix 2A for a more detailed discussion of part complexity and interconnectedness.

develop the part and the equipment used to manufacture the die are specialized to the auto maker, and thus determines the holdup problem. If a die is designed for a part which is relatively simple to manufacture and the parts are not tightly connected, there is no holdup problem - many suppliers and manufacturers can be found. The case considered by Klein et al. (1978), where both the manufacturer and the supplier face significant holdup possibilities, is appropriate if the part in question is extremely complex and the parts are tightly interconnected. However, there are other cases in which part characteristics and holdup are different. In this context, it is useful to examine the wide range of contracting arrangements in the auto industry for die development, many of which are not explained using a model focused solely on physical asset ownership.

This section presents examples of contracting over die development where part characteristics vary, and serve as determinants of the possibility of rent appropriation by the contracting parties. A series of cases provide evidence for the relevance of part characteristics as key factors in ownership and access arrangements. For confidentiality reasons, study company names are not disclosed.[4]

Supplier 1, an independent die supplier, designs and produces dies for body panels, which it then sells to auto manufacturers such as Manufacturer A, as shown in Figure 2.2.2. Supplier 1 produces the dies using its own tooling and stamping equipment. The dies are developed for parts which have very sharp corners, and features such as a deep depression for the door handle. The straight lines of the parts create a clean interface with the rest of the body, but such corners can wrinkle and tear during manufacture. Thus, I interpret such dies as highly complex, but not tightly interconnected with other body parts.[5] They are manufactured using a standard multipurpose stamping press. Supplier 1 will design tooling to fit the dies to their own stamping press. The extent to which Supplier 1 optimizes the tooling with the dies and the press is non-contractible. After prototype parts

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[4] See Appendix 2A for more details on study companies and on data collection.

[5] See Appendix 2A for a detailed description of part complexity and interconnectedness.

are produced, the assembled body is crash-tested, resulting in 30-60% changes in the Supplier 1 dies.

In order to encourage Supplier 1 to make this specific investment, Manufacturer A signs contracts with an exclusivity clause, contractually removing the possibility of Manufacturer A switching to another supplier in order to change the dies after the crash test. The contract sets an historically-based estimate of cost of changes after the crash test in advance. That is, for such dies in the past, crash tests have resulted in 30 - 50% of changes to the die, and the contract includes an estimate on the cost of such changes. However, this agreement does not prevent Supplier 1 from negotiating a higher cost of changes with Manufacturer A, as it is impossible to predict resulting changes with certainty, and the companies are unable to predict the difficulty of changing the dies and tooling. Unlike the Fisher-General Motors example, Manufacturer A has not elected to purchase Supplier 1. In fact, Supplier 1 is a spin-off of Manufacturer A.

Manufacturer A positions key die employees on site at Supplier 1. Manufacturer A has internal diemaking capability. In interviews, Manufacturer A managers indicated that their Supplier 1-based employees maintain a working knowledge of specific die production that would allow Manufacturer A to make die changes internally should they ever run into difficulty with Supplier 1.

The previous analysis focuses on dies which are not highly interconnected. Both Manufacturer B and Manufacturer A feature vehicles with body panels which are designed with clean lines, which I interpret as low interconnectedness. However, the Supplier 1-Manufacturer A relationship differs from that of Manufacturer B and its key die supplier, Supplier 2, as does the complexity of the dies themselves. I will now examine Manufacturer B's relationship with Supplier 2 in the context of its part characteristics.

Supplier 2 is an independent die supplier. Supplier 2 designs and produces dies for body panels, which it then sells to auto manufacturers such as Manufacturer B. Supplier 2 produces the dies using its own tooling and stamping equipment. The dies are developed for parts with rounded edges and shallow depth, using lightweight steel. Such shapes conform to the natural properties of sheet metal, thus they are relatively easy to manufacture. The parts are designed to be modular relative to other panels. According to my measures, such dies are simple, and not interconnected.

As such dies are simple and part of Supplier 2's basic product offering, they are purchased using historically-based estimates of cost of changes, without exclusivity clauses. The fact that the dies are simple and relatively easy to change creates the possibility for easy switching by Manufacturer B. As the parts are not interconnected, Supplier 2 has little opportunity to negotiate higher cost of changes. Manufacturer B also has internal diemaking capability. For such dies, Manufacturer B does not send employees to the Supplier 2 site. Instead, the parts are shipped directly from Supplier 2 to Manufacturer B once the dies have been developed.

Manufacturer B's dies are relatively simple to manufacture, as are the dies that Manufacturer C chooses to outsource to its key supplier, Supplier 3, an independent die supplier. In Manufacturer C's case, however, the parts are tightly interconnected in order to support its aerodynamic body design. Where Manufacturer B chooses to purchase dies manufactured on Supplier 2 equipment, Manufacturer C loans its internal stamping presses to Supplier 3 for development.

The Manufacturer C body panels are shallow in depth but feature shapes such as an angled door frame which, while not complicated to manufacture, must be flush with several other panels at various points. According to my measures such dies are simple and interconnected. Supplier 3 often produces the dies using Manufacturer C-owned tooling and stamping equipment, which Manufacturer C loans to the Supplier 3 for the development period, and then transfers back to its own plants once production is underway.

Manufacturer C managers indicated that in the past, parts produced with dies manufactured on Manufacturer C equipment were more likely to fit with the rest of the

Manufacturer C body system once production was underway. This is because all stamping equipment is slightly different, and the managers felt that tooling developed on production equipment would create less variation. The managers indicated that loaning extremely valuable stamping equipment encouraged Supplier 3 to make this specific investment, as Manufacturer C is less likely to switch to an outside supplier once they have committed equipment to the Supplier 3 plant. The managers also indicated that they felt that their ability to reclaim the press at any time keeps Supplier 3 from negotiating for higher cost of changes. In the Manufacturer C, as well as in the Manufacturer B and Manufacturer A cases, the asset ownership arrangements for die contracting do not fit the picture of vertical integration suggested by the Klein et. al description of General Motors and Fisher Body. However, Manufacturer D produces dies for exterior body panels in-house.

Manufacturer D produces dies for body panels in-house for its luxury vehicle line. Such parts feature heavy reinforced steel, making them extremely difficult to form. The parts are also designed to minimize body mass, requiring them to be tightly interconnected. Company executives indicated that such parts, which comprise the exterior sheet metal of the car, are the key to its styling, and thus to its market position. As such, the executives indicated that they felt that allowing an outside supplier to develop dies for such parts would leave the firm much too vulnerable to price gouging.

In summary, the existing literature on die contracting in the auto industry cannot account for the wide range of contracting practices in modern auto manufacture. Based on the data I collected and interviews I conducted in the auto industry, in the next section I propose a model of contracting focusing on part characteristics in order to refine the sources of holdup faced by the contracting parties.

3. The Benchmark Model: The Property Rights Approach

The previous examples suggest several features of the contracting environment are important in explaining relationship-specific investments in auto parts development: part complexity and interconnectedness, ownership of key physical assets such as the dies and stamping press, and employee access to those assets. In this section, I add parameters for complexity and part interconnectedness to the standard Grossman-Hart-Moore framework in order to capture how investment by the contracting parties varies under different ownership structures. Following Grossman-Hart (86), the focus in this section is on physical asset ownership - how ownership of the dies and stamping equipment affects investment incentives by the manufacturer and die supplier. I demonstrate that the property rights approach, incorporating measures of part complexity and interconnectedness, is appropriate for explaining investment decisions in die contracting for situations where part characteristics covary. However, contracting situations such as described in the Manufacturer A and Manufacturer C cases, remain unexplained by this approach.

I consider the problem of bilateral contracting between the manufacturer M and an individual supplier S over the latter's participation in the product development process for a component in an automotive subsystem. In this model, the crash test reveals necessary part changes which are noncontractible ex ante. The action taken at this decision node will be denoted as $u \in$ (restamp, stop), where "stop" is termination of the project. To govern this foreseeable event, the date 0 contract allocates a residual right of control over the dies and stamping equipment to one of the two parties, henceforth the ``owner'' of that asset.

Timing

The product development process takes place over three periods, dates 0, 1, and 2, illustrated in Figure 2.3.1. The manufacturer dictates the terms of the date 0 contract, subject to a reservation wage for the supplier, normalized to zero for simplicity. The holdup story is summarized in the following timeline[6]:

Date 0: The manufacturer proposes a contract that specifies ownership of the stamping equipment and a monetary transfer between the two parties. The supplier accepts or rejects this contract.

Date 1: The manufacturer and supplier simultaneously make their respective investments in stamping skills. Prototype parts are produced using a unique physical asset, the stamping press. A monetary transfer is paid.

Date 2: The crash test reveals improvements needed. The parties bargain over whether or not to continue their relationship into the quality control phase. If not, the stamping equipment reverts to its owner, and the two parties claim their outside option values for the current period.

Bargaining

As in Hart and Moore (1990), renegotiation is assumed to be costless and efficient. Surplus at the date 2 negotiation is divided according to the Shapley value. Payoffs will be measured in date 2 dollars. I also assume that both the manufacturer and supplier are risk-neutral, and thus each party will maximize the net value of her date 2 payoff.

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[6] This section informally describes an incomplete contracting interpretation of the auto development process. A typical auto development process consists of seven stages: (1) choice of performance targets; (2) subsystem design; (3) outsourcing of dies for individual parts; (4) part prototyping and assembly; (5) crash test; (6) quality control; and (7) product launch. This paper focuses on a subset of the product development process, in the middle of the third stage, after the manufacturer has contracted out the production of all new dies, but before those dies have been delivered.

Ownership

I assume that either party can own the dies and stamping press (henceforth the "asset") required for production of the part.[7] Both the manufacturer and the supplier have to make an investment specific to the asset, in the form of specializing their human capital (e.g. learning to overcome the design challenges associated with a particular component.)

As in Grossman-Hart (86) and Hart-Moore (90), each party's best alternative to a negotiated agreement in period 2 depends upon that party's ownership of the physical asset - the dies and stamping equipment. If the parties do not agree to continue their relationship, a sole owner of the asset redeploys it in its best alternative use. If both parties own the asset, it has no outside value, as it cannot be divided. I focus on three ownership structures in this section:

Integration: the manufacturer owns the asset
Non-Integration: the supplier owns the asset
Joint Ownership: the manufacturer and supplier jointly own the asset

I focus on these three cases as these are the ownership structures considered by Grossman-Hart-Moore. Other possible ownership structures are discussed briefly at the end of this section.

Investment

The costs and benefits of the alternatives available at the renegotiation stage have three parameters: the players' date 0 skill investments i_j; the predetermined degree of complexity of the part design, represented as a continuous-valued scalar $\theta \in [0,1]$ and the

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[7] As described in the previous section, the dies and the stamping press are highly complementary assets. I assume that the dies and stamping are owned together in this model.

interconnectedness γ of the part with the rest of the body system, also represented as a continuous-valued scalar $\gamma \in [0,1]$. I discuss the parameter assumptions in the next section. Following Hart-Moore (1990) and Rajan-Zingales (1998), I focus on investment actions i_j, j=(M,S) faced by the contracting parties in human capital.[8] For maximum tractability, i_j are both the level of investment and the investing party's private cost of investment.

The value to the manufacturer of a correctly fitted part is $R(i_M)$. If trade occurs, joint surplus is $R(i_M) - C(i_s)$, where $C(i_s)$ is the cost of changing the die. If trade does not occur, I assume that under integration, the manufacturer could recut the die and restamp the part himself to obtain the same gross value from the refitted part, minus a market recutting cost $\hat{c}$, where $\hat{c}>C(.)$. Thus the manufacturer faces an ex post payoff of $R(i_M) - \hat{c}$. If the manufacturer does not own the asset and trade does not occur, I assume that he can purchase a part from an outside supplier. However, I assume that this part will be less well - suited to the project given the reduced development time, with a value to the manufacturer of $r(i_M,\gamma,\theta)$, where $R(i_M) > r(i_M,\theta, \gamma)\ \forall\gamma,\theta$. Thus the manufacturer will face an ex post payoff of $r(i_M,\gamma,\theta) - \hat{c}$ in the nonintegration case. In the event of joint ownership, I assume that the manufacturer cannot divide and use his half of the equipment. Thus, he faces the same outside option as in supplier ownership, with an ex post payoff of $r(i_M,\gamma,\theta) - \hat{c}$.

The supplier's production costs are $C(i_s)$. If trade does not occur, I assume that the supplier trades with the market at a price $\hat{r}$ where $\hat{r} < R(i_M)\ \forall i$. In the case of integration, I assume that the supplier cannot fully redeploy her skills, for an ex post payoff of $\hat{r}$- $c(i_s,\theta)$, where $c(.,\theta) > C(.)$, reflecting the higher cost of applying her skills to an outside project at a later date.

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[8] Rajan and Zingales (1998) allow for investment to be in either human or physical capital. The focus here,

If trade does not occur in the nonintegration case, I assume that the supplier could immediately employ the asset at an alternative use, for an ex post payoff of $\hat{r}$-$C(i_s)$. In the event of joint ownership, I assume that the supplier cannot divide and use her half of the equipment, thus her outside option is the same as under integration, with an ex post payoff of $\hat{r}$-$c(i_s,\theta)$.

Even under the least favorable conditions, however, I assume that project continuation is optimal:

(3.1) $R(.) > r > \hat{r}(.)$

(3.2) $\hat{c} > c(.) > C(.)$

I assume positive returns to investment in skills if trade occurs and concavity/convexity,

(3.3) $R'(i_M) > 0,\ R''(i_M) < 0$

(3.4) $C'(i_s) < 0,\ C''(i_s) > 0$

I assume negative outside returns to supplier skill investment:(3.5) $c_{i_s} > 0$, as the supplier will be less able to fully apply her project-specific skills to an outside project. I assume that manufacturer investment in skills matters more for outside options than inside for all levels of part interconnectedness and complexity, as increasing design capability improves the likelihood of adapting those skills to another project.

$r'(i_M) > R'(i_M) \forall \gamma, \theta$.

I assume that part interconnectedness does not affect the manufacturer's returns to investment in skills if trade occurs, as increasing interconnectedness should not affect the apply of the manufacturer to apply his skills in the project for which they were acquired. I assume that part interconnectedness increases the outside returns to investment by the manufacturer, as having the ability to coordinate an interconnected part should improve the

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as with Grossman-Hart (1986) and Hart-Moore (1990) is on investment in human capital only.

manufacturer's ability to utilize his skills to integrate an outside part with the rest of the system.

(3.6) $R_{i_m,\gamma} = 0$

(3.7) $r_{i_m,\gamma} > 0$.

If trade occurs, I assume that that part complexity does not affect the returns to investment in skills, as increasing complexity does not affect the ability of the manufacturer or the supplier to fully utilize their relationship-specific skills:

(3.8) $R_{i_m,\theta} = 0$

(3.9) $Ci_{s,\theta} = 0$

However, I assume that part design complexity reduces the outside return to project-specific skills for manufacturer and the supplier for the following reasons: specializing in an increasingly complex design reduces the ability of the manufacturer to fully utilize those skills for part changes with another supplier. Similarly, if the supplier invests in highly complex designs, it will be difficult to fully utilize those skills in market projects.

(3.10) $r_{i_m,\theta} < 0$

(3.11) $c_{i_s,\theta} > 0$

The parameter assumptions are summarized in Table 2.3.1

The first-best Allocation

The benchmark for analysis of the pure property rights model is the first-best case in which both the ex ante skill investments and the ex post continuation decision are contractible. In this case, both parties maximize the net present value of their relationship:

(3.10) $R(i_M) - C(i_s) - i_m - i_s$

By concavity of R(.), convexity of C(.), the first order conditions, sufficient for maximizing (3.10) are :

$R'(i_m^{FB}) = 1$

$|C'(i_s^{FB})| = 1$

The second-best levels of investment

Manufacturer Ownership

In this case, disagreement at date 2 would lead the manufacturer to pursue quality control under his own cost structure, while the original supplier would face temporary unemployment of her skills. Then the manufacturer and supplier's payoffs, net of investment costs are given by:

(3.11) $R(i_M) - 1/2\, C(i_s) - 1/2\, \hat{c} - i_m$

While the die supplier maximizes:

(3.12) S: $1/2 R(i_M) + 1/2\, \hat{r} - 1/2\, C(i_s) - 1/2 c(i_s, \theta) - i_s$

The first order conditions for maximizing 3.11 and 3.12 are:

(3.13) $R'(i_m^M) = 1$

(3.14) $|1/2 C'(i_s^M)| + 1/2 |\, c'(i_s^M)| = 1$

Thus the manufacturer has first-best investment incentives and the supplier underinvests under integration.

Supplier ownership

In this case, disagreement at date 2 would lead the supplier to divert the asset to a less productive use, while the manufacturer would face stiff resourcing costs. The parties then maximize the following returns:

(3.15) $M: 1/2R(i_M) + 1/2r(i_M, \theta, \gamma) - 1/2\, C(i_s) - 1/2\, \hat{c} - i_m$

(3.16) $S: 1/2R(i_M) + 1/2\, \hat{r} - C(i_s) - i_s$

The first order conditions for maximizing (3.15) and (3.16) are:

(3.17) $R'(i_m^S) + r'(i_M^S) = 2$

(3.18) $|C'(i_s^S)| = 1$

In this case, the manufacturer has an incentive to overinvest and the supplier maintains first-best investment incentives. This result can be interpreted as follows: If the supplier owns he will invest optimally. However, under supplier ownership the manufacturer is concerned about the possibility of holdup, and thus invests in skills in order to improve his ability to make the needed changes should negotiation break down. This results in overinvestment.

Joint Ownership

In this case, the parties jointly own the equipment, and as it cannot be divided, both parties face outside options which are the same as under the respective non-ownership cases. Thus, as in (3.12) and (3.15), the parties maximize the following returns:

(3.19) $M: 1/2R(i_M) + 1/2r(i_M, \theta, \gamma) - 1/2\, C(i_s) - 1/2\, \hat{c} - i_m$

(3.20) $S: 1/2R(i_M) + 1/2\, \hat{r} - 1/2\, C(i_s) - 1/2c(i_s, \theta) - i_s$

The first order conditions for maximizing (3.19) and (3.20), as in (3.14) and (3.17) are :

(3.21) $R'(i_m^{JT}) + r'(i_M^{JT}) = 2$

(3.22) $|C'(i_s^{JT})| + |c'(i_s^{JT})| = 2$

Thus, Joint Ownership is strictly suboptimal as this structure gives overinvestment incentives to the manufacturer and underinvestment incentives to the supplier. The first-best outcome, and the second-best outcomes under integration, nonintegration and joint ownership is illustrated in figures 2.3.2. This yields the following comparative statics:

$i_m^M = i_m^{FB} < i_m^{JT} = i_m^S$

$i_s^M = i_s^{JT} < i_s^{FB} = i_s^S$

As opposed to the pure Grossman-Hart-Moore model where both parties tend to underinvest, I have assumed that given part characteristics, the manufacturer has an incentive to overinvest and the supplier faces underinvestment incentives. Again, this is because I assume that part interconnectedness increases the outside returns to investment in skills for the manufacturer, and thus creates an incentive to overinvest.

Proposition 1:

Fixing θ, as γ increases, under assumptions (3.1), (3.2), (3.6) and (3.7), the benefits to manufacturer ownership are increasing.

Proof:

The loss under Integration, $\pounds 1$, is $[-C(i_s^{FB})- i_s^{fB}] - [- C(i_s^M)- i_s^M]$, which is constant in γ.

The loss under Nonintegration, $\pounds 2$, is $[R(i_m^{FB}) - i_m^{FB}] - [R(i_m^S) - (i_m^S)]$.

As γ increases, the loss under integration is not affected. For nonintegration:

By assumption 3.6, $\frac{\partial \pounds 2}{\partial \gamma} = - \frac{\partial}{\partial \gamma} i_m^S[R_i(i_m^S)- 1]$.

By assumption 3.7 $\frac{\partial}{\partial \gamma} [i_m^S]>0$.

Since R is concave, $[R_i(i_m^S)- i_m^S]$ is concave, with maximum at i^{FB}.

This, along with assumption 3.7 implies that at $i^S > i^{fB}$, $\frac{\partial}{\partial i_M} [R_i(i_m^S)- i_m^S]<0$.

Thus, $\frac{\partial \pounds 2}{\partial \gamma} > 0$. □

As γ increases, the manufacturer's incentive to overinvest is increased, and the supplier's incentive to underinvest under integration is not affected, suggesting that the manufacturer should own as interconnectedness increases.

Proposition Two:

Fixing γ, as θ increases, under assumptions (3.9) and (3.11), the benefits to supplier ownership are increasing.

Proof:

The loss under Integration, $\pounds 1$, is $[-C(i_s^{fB})- i_s^{FB}] - [- C(i_s^{M})- i_s^{M}]$.

The loss under Nonintegration, $\pounds 2$, is $[R(i_m^{fB}) - i_m^{fB}] - [R(i_m^{S}) - i_m^{S}]$.

For Integration:

By assumption 3.9, $\frac{\partial \pounds 1}{\partial \theta} = -\frac{\partial}{\partial \theta} i_s^{M}[- C_i(i_s^{M})- 1]$.

By assumption 3.11 $\frac{\partial}{\partial \theta} [i_s^{M}]<0$.

Since C is convex, $[- C_i i_s^{M})- 1]$ is concave, with maximum at i_s^{FB}.

This, along with assumption 3.11, implies that at $i_s^{M} < i_s^{FB}$, $\frac{\partial}{\partial i_s} [- C(i_s^{M})- 1] >0$

Thus $\frac{\partial \pounds 1}{\partial \theta} > 0$.

For Nonintegration:

By assumption 3.8, $\frac{\partial \pounds 2}{\partial \theta} = - \frac{\partial}{\partial \theta} i_m^{S}[R_i(i_m^{S})- 1]$

By assumption 3.10 $\frac{\partial}{\partial\theta}$ [i_m^S]<0

Since R is concave, [$R(i_m^S)$- 1] is concave, with maximum at i^{FB}.

This, along with assumption 3.10, implies that at $i^S > i^{FB}$, $\frac{\partial}{\partial i_M}$ [$R(i_m^S)$-1]<0.

Thus $\frac{\partial \mathcal{L}2}{\partial\theta} < 0$. □

Increasing complexity reduces the manufacturer's overinvestment problem and exacerbates the supplier's underinvestment problem, thus the supplier should own.

Conclusion

An interpretation of the auto industry integration decision from the pure property rights model is consistent with the product development characteristics that underlie the contracting problem: that is, greater parts interconnectedness increases the coordination costs faced by the manufacturer, creating greater possibility for holdup by the die supplier. Therefore, as part interconnectedness increases, firms are more likely to vertically integrate. The preceding analysis demonstrates that part interconnectedness increases the manufacturer's tendency to overinvest in skill acquisition for supplier-owned equipment in order to protect himself against potential holdup by the supplier. Similarly, part complexity increases the potential of manufacturer holdup, and increases the supplier's tendency to underinvest under integration as she is less likely to capture her share of the resulting project surplus. Empirical observation of sourcing practices suggest that prevalence of intermediate governance categories such as joint ownership are also affected by the information structure characterized by access to critical resources as well as by asset ownership. I now focus on how the overinvestment and underinvestment incentives of the contracting parties are affected by access to critical resources.

4. Ownership and Access

In this section, access to critical resources is considered as another instrument affecting ex ante investment decisions. The benchmark property rights model assumes that ownership automatically grants access, I now consider the possibility of asset ownership without access and access without asset ownership. I demonstrate that access to critical resources, more significantly denying access to critical resources, can be used as another mechanism for motivating ex ante investment incentives.

The classic property rights model assumes that all parties have the opportunity to make specific investments. Rajan and Zingales (1998) argue for an extended view in which the owner of the assets can deny non-owning parties the opportunity to make specific investments. As modeled here, the parties jointly decide access in the date 0 contract. This notion of access is simplified from that of Rajan and Zingales (1998) in that I only consider investments in human capital, as opposed to human and physical capital.

As in Rajan-Zingales (1998), I assume that since investment is specific to the machine and its use, that neither party can make the investment if she does not have access to the critical asset. Why might this option be preferred? As shown in the benchmark case, under certain contracting structures, the manufacturer has an incentive to overinvest. I demonstrate that removing access can restore proper investment incentives for contracting over parts with high complexity and low interconnectedness as well as for contracting over parts with low complexity and high interconnectedness.

The modified timeline is as follows:

Date 0: The manufacturer proposes a contract that specifies ownership and access to the stamping equipment and a monetary transfer between the two parties. The supplier accepts or rejects this contract.

Date 1: The manufacturer and supplier simultaneously make their respective investments in stamping skills. Prototype parts are produced using a unique physical asset, the stamping press. A monetary transfer is paid.

Date 2: The crash test reveals improvements needed. The parties bargain over whether or not to continue their relationship into the quality control phase. If not, the stamping equipment reverts to its owner, and the two parties claim their outside option values for the current period.

I focus on four ownership structures in this section:

Integration: the manufacturer owns the asset, the supplier does not have access
Non-Integration: the supplier owns the asset, the manufacturer does not have access
Keiretsu Ownership: the supplier owns the asset and the manufacturer has access
Equipment Loan: the manufacturer owns the asset, the supplier has access

In this model, keiretsu ownership and equipment loans are intermediate categories of ownership. This notion of intermediate ownership differs from the strict Grossman-Hart-Moore notion of joint ownership, where both parties jointly own equipment and implicitly both parties have access. However, I focus on these forms of intermediate ownership as they correspond directly to empirically observed contracting arrangements in the auto industry.

The first-best result is unchanged from (3.1). If trade does not occur, and the manufacturer does not have access to the equipment, his ex post payoff is 0. If trade does not occur, and the supplier does not have access, his payoff is 0.

Manufacturer ownership, Supplier Access

In this case, the results are as in the benchmark model of integration. Disagreement at date 2 would lead the manufacturer to pursue quality control under his own cost structure, while the original supplier would face temporary unemployment of her skills. Under division of surplus according to the Shapley Value, the first order conditions, as for maximizing (3.2) and (3.3) are:

(4.1) $R'(i_m^{MA}) = 1$

(4.2) $1/2|C'(i_s^{MA})| + 1/2|c'(i_s^{MA})| = 1$

Thus the manufacturer has first-best investment incentives and the supplier underinvests under manufacturer ownership.

Supplier ownership, Manufacturer Access

Again, the results are unchanged from the benchmark model of nonintegration. In this case, disagreement at date 2 would lead the supplier to divert the asset to a less productive use, while the manufacturer would face stiff resourcing costs. The first order conditions, as for maximizing (3.6) and (3.7) are:

(4.3) $R'(i_m^{SA})+r'(i_M^{SA}) = 2$

(4.4) $|C'(i_s^{SA})|=1$

In this case, the manufacturer has an incentive to overinvest and the supplier maintains first-best investment incentives.

Manufacturer ownership, Supplier Does Not have Access (Integration)

In this case, disagreement at date 2 would lead the manufacturer to pursue quality control under his own cost structure, while the original supplier would be unable to apply her skills, facing an ex post payoff of $-i_s$.

The first order conditions are:

(4.5) $R'(i_m^{INT}) = 1$

(4.6) $C'(0) = 0$

Thus the manufacturer has first-best investment incentives and the supplier does not invest at all.

Supplier ownership, Manufacturer does not have Access (Nonintegration)

In this case, disagreement at date 2 would lead the supplier to divert the asset to a less productive use, while the manufacturer would face stiff resourcing costs. In this case, the manufacturer faces a payoff of $-i_m$. The first order conditions are:

(4.3) $R'(0) = 0$

(4.4) $C'(i_s^{NON})=1$

In this case, the supplier has first-best investment incentives, and the manufacturer does not invest at all.

The first-best outcome, and the second-best outcomes under integration, nonintegration and ownership with access and access without ownership are illustrated in figure 2.4.1 This yields the following comparative statics:

$i_m\ (NON) < i_m\ (MA) = i_m\ (INT) = i_m\ (FB) < i_m\ (SA)$

$i_s\ (INT) < i_s\ (SA) < i_s\ (NON) = i_s\ (FB) = i_s\ (MA)$

Proposition Three:

Conditional on Supplier Ownership, increasing part interconnectedness makes access undesirable and an increase in complexity makes access preferable.

Proof:

Given supplier ownership, the difference in the surplus with and without access, *S*, is

$$R(i_{in}^{S}) - i_m^{S} - R(0).$$

By assumption 3.6, $\frac{\partial S}{\partial \gamma} = \frac{\partial}{\partial \gamma}[i_{in}^{S}]\frac{\partial}{\partial i_M}[R(i_m^{S}) - i_m^{S}]$.

By assumption 3.7 $\frac{\partial}{\partial \gamma}[i_m^{S}] > 0$

R is concave with maximum at i^{FB}. This, along with assumption 3.7 implies that at

$i_m^{S} > i_m^{fb}$, $\frac{\partial}{\partial i_M}[R(i_m^{\prime}) - i_m^{S}] < 0$.

Thus, $\frac{\partial S}{\partial \gamma} > 0$.

The loss under access is increasing as γ increases.

By assumption 3.8, $\frac{\partial S}{\partial \theta} = \frac{\partial}{\partial \theta}[i_m^{S}]\frac{\partial}{\partial i_M}[R(i_m^{S}) - 1]$.

By assumption 3.10 $\frac{\partial}{\partial \theta}[i_m^{S}] < 0$

R is concave, with maximum at i^{fb}. This, along with assumption 3.10 implies that

at $i_m^{S} > i_m^{fb}$, $\frac{\partial}{\partial i_M}[R(i_m^{S}) - i_m^{S}] < 0$.

Thus, $\frac{\partial S}{\partial \theta} < 0$. □

The loss under access is decreasing as θ increases.

Proposition Four:

Conditional on Manufacturer Ownership, a change in part interconnectedness does not affect access, but an increase in part complexity makes supplier access undesirable.

The surplus with access - surplus without access, $\mathcal{M}$, is $[-C(i_s^M) - i_s^M] - [-C(0)]$,

which is constant in γ.

By assumption 3.9, $\frac{\partial \mathcal{M}}{\partial \theta} = \frac{\partial}{\partial \theta}(i_s^M)\, \frac{\partial}{\partial i_s}[-C(i_s^M) - i_s^M]$.

By assumption 3.11 $\frac{\partial}{\partial \theta}[\, i_s^M] > 0$.

C is convex, with minimum at i^{fb}. This, along with assumption 3.11, implies that

at $i_s^M < i_s^{fb}$, $\frac{\partial}{\partial i_s}[-C(i_s^M) - i_s^M] > 0$.

Thus $\frac{\partial \mathcal{M}}{\partial \theta} > 0$. □

The loss under access is increasing as θ increases.

Conclusion

In this section it is shown that when the supplier owns, giving access to the manufacturer is only useful when parts are complex but not interconnected because he will further overinvest with access if parts are interconnected. Similarly if the manufacturer owns, giving the supplier access worsens her investment incentives if parts are complex. This result has important implications for explaining intermediate categories of ownership. This characterization leads to a two by two matrix of outcomes, as shown in Figure 4.1.

The Grossman-Hart-Moore model captures the contracting problem in the auto industry as shown in the diagonal categories in Figure 4.1, i.e. when part complexity and interconnectedness covary. With access, manufacturer ownership is preferable for interconnected parts and supplier ownership is preferable for complex parts. As discussed in Section Two, arrangements such as manufacturer owns, no access and supplier owns no access are common contracting practices in the auto industry. The results of this section suggest an explanation for why we see these intermediate categories of ownership.

5. Implications of the Effects of Ownership and Access

The results of the alternate model suggest that access exacerbates the incentive of the manufacturer to overinvest if parts are interconnected, and the incentive of the supplier to underinvest if parts are complex. This conclusion has important implications because it links part characteristics to the desirability of intermediate categories of ownership.

In the Section Two examples, Manufacturer A and Manufacturer B contract with die suppliers under the same ownership structure, but their level of access differs. Manufacturer A has access without ownership. That is, Manufacturer A employees work at the Supplier 1 site with the Supplier 1 equipment during the project. Manufacturer B has no access and no ownership - only Supplier 1 employees work on the Manufacturer B project at the Supplier 1 site.

In these cases, as the part in question is not interconnected, physical asset ownership by the supplier is reasonable. For Manufacturer A, given that the part is complex but not interconnected, having access reduces overinvestment incentives by Manufacturer A without affecting supplier incentives. Thus a "don't own, access" structure is optimal for such product development. For Manufacturer B, a spot market transaction is preferable given the product characteristics. That is, given that the part in question is simple and not interconnected, access does not improve investment incentives. This example helps to explain how part characteristics, ownership of and access to critical resources interact in determining firm incentives.

In the cases of Manufacturer C and Manufacturer D, both manufacturers own the physical assets, but where Manufacturer C chooses to loan equipment, providing the supplier, Supplier 3, with access, Manufacturer D produces in-house. The Manufacturer D example is similar to the Klein et al. description of the GM-Fisher Body example. For a case where the part is complex and interconnected, the parties face two-way holdup problem which is resolved by integration. In contrast, for a simple but interconnected part, the supplier has little opportunity to holdup manufacturer development. For Manufacturer C, giving access to the supplier for a simple but interconnected part improves Supplier 3's incentive to invest, thus a manufacturer owns, supplier access contract is reasonable.

Extensive interviews with die suppliers and auto makers indicate that part characteristics greatly affect the extent to which development can be held up by the contracting parties, and thus affects their ex ante investment incentives. This model adds insight into modern manufacturing practices by incorporating measures of part characteristics into a formal model of ownership.

The prevalence of intermediate categories of ownership in the auto industry is a result of the interaction of the two choices, ownership of and access to physical assets, with the environment and with each other. Such dynamics should be present in other manufacturing industries as well.

In summary, the model proposed in this paper can be applied in a contracting environment where product characteristics vary, such as in computer software, semiconductors and photolithography equipment. This approach allows for a refined measurement of the holdup problem faced by the contracting parties, and for further examination of how ex ante investment incentives are affected under various ownership and access structures.

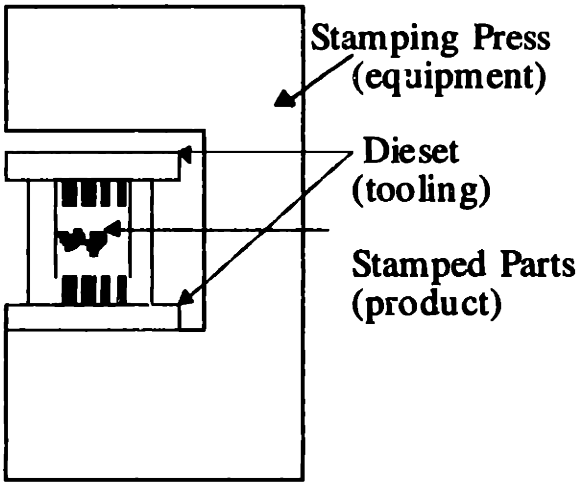

Figure 2.2.1 Auto Body Part Production Equipment

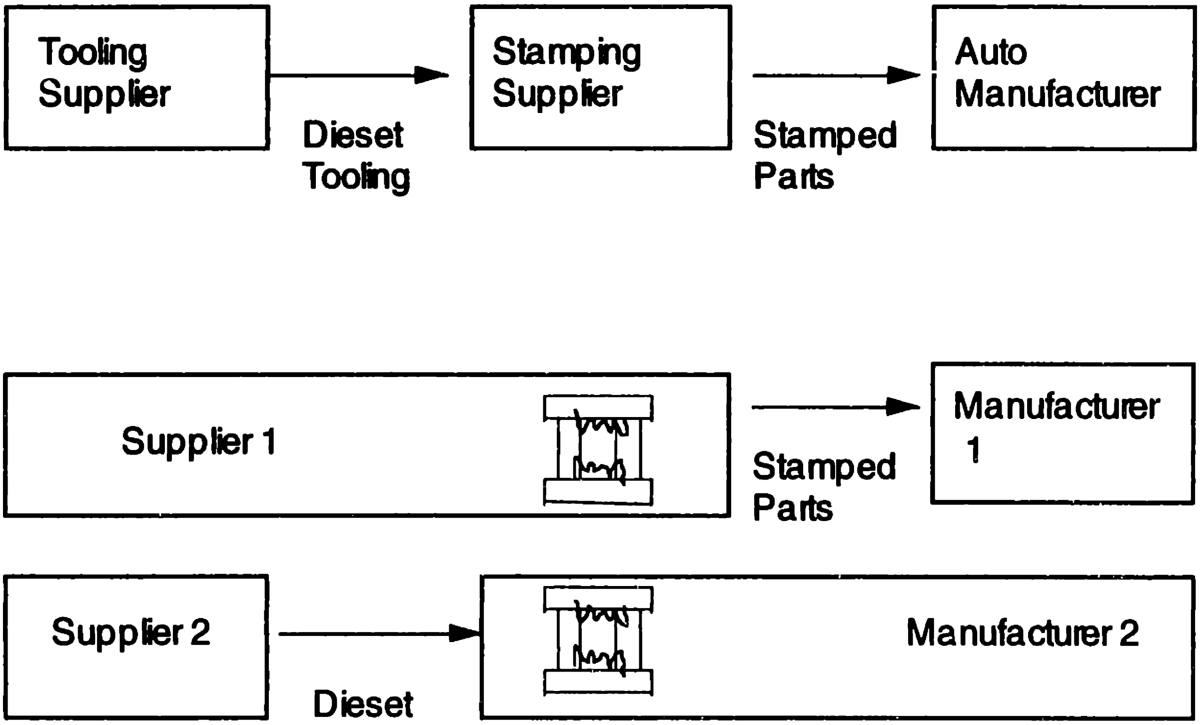

Figure 2.2.2 The Auto Industry Supply Chain

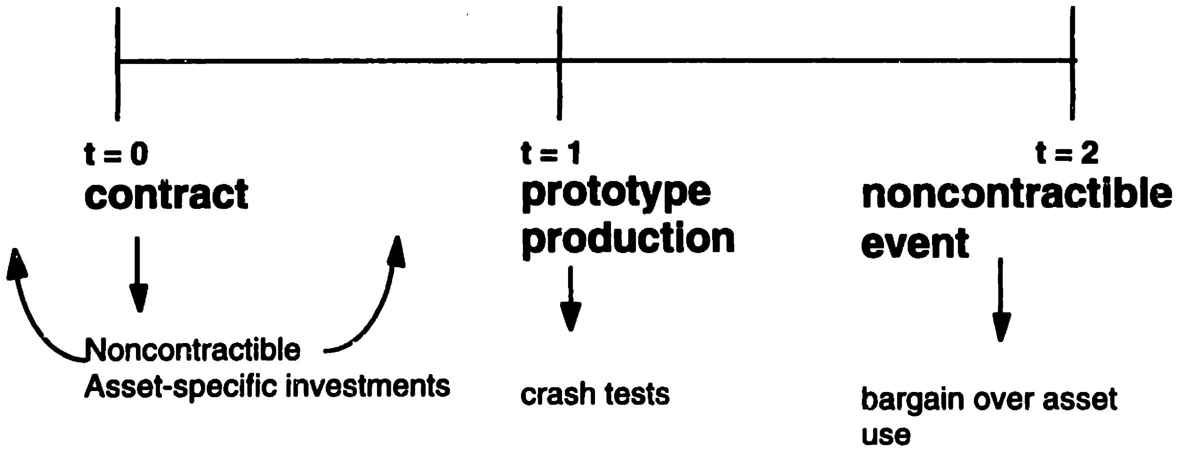

Figure 2.3.1 Benchmark Model Contracting Timeline

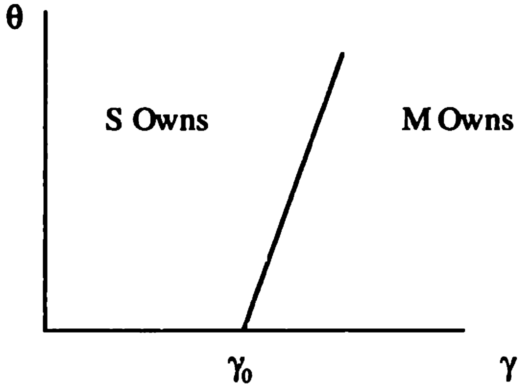

Figure 2.3.2 Ownership in Benchmark Model

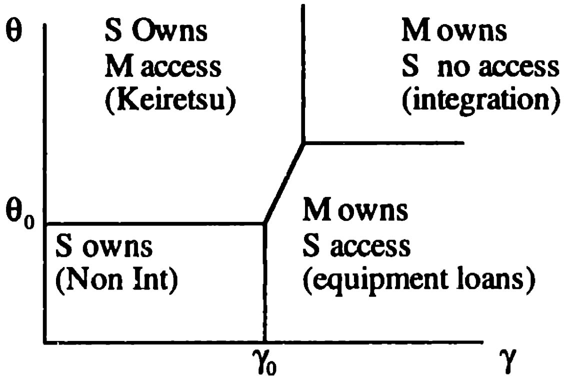

Figure 2.4.1 Ownership and Access

	ASSUMPTION	INTERPRETATION
Revenue **3.3**	$r'(i_M) > R'(i_M) > 0$ $r''(i_M) < 0, R''(i_M) < 0$	positive returns to investment in skills concavity
3.8	$R_{i_M,\theta} = 0$	part complexity does not affect the inside returns to investment in skills
3.6	$R_{i_M,\gamma} = 0$	part interconnectedness does not affect the inside returns to investment in skills
3.10	$r_{i_M,\theta} < 0$	part complexity decreases the outside returns to investment in skills
3.7	$r_{i_M,\gamma} > 0$	part interconnectedness increases the outside returns to investment in skills
Cost **3.4**	$C'(i_s) < 0$ $C''(i_s) > 0$	positive returns to inside investment in skills convexity
3.5	$c'(i_s) > 0$ $c''(i_s) < 0$	negative returns to outside investment in skills, convexity
3.9	$C_{i_s,\theta} = 0$	part complexity does not affect the inside returns to investment in skills
3.11	$c_{i_s,\theta} > 0$	part complexity decreases the outside returns to investment in skills

Table 2.3.1 Model Assumptions

Appendix 2A. Data Selection and Parameter Definitions

This Appendix provides a brief overview of the methods used to evaluate die complexity and interconnectedness. This description is based on an original study of parts contracting for the luxury performance vehicle segment of the auto industry, defined by *Consumer Reports* as vehicles above $30,000 in 1995. As this segment represents the flagship vehicles for the auto companies it is thought to provide the most powerful and comparable test of the possibilities available to auto firms in both product design and production. 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.

This original dataset covers components in eight vehicles 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. All interviews were conducted in the native language of the company engineers.

This section focuses on the automobile body-in white, which includes all of the sheet metal and sheet metal processing in the car, about 200 sheet metal stampings. A set of dies for a single body panel can cost more than two million dollars, and die development is typically the longest lead time item in the automobile product development process. For each die for each exterior body panel in the sample, detailed part drawings were obtained, as well as information on the number of hits (stamping processes) for the most complex part, the material used, and design considerations.

Die Design Complexity

The design of a part generates information in the form of drawings, equations, material specifications and operational instructions. Suh, Chryssolouris, Gutowski, Sachs and Cook (1990) define part information content as a "measure of complexity involved in achieving a given task." In order to evaluate die design complexity, I focused on the following elements:

1. Material Properties - I used the characteristics of metal important in sheet forming in order to evaluate die complexity (Kalpakjian, 1992). These include elongation - the capability of the material to stretch without necking; residual stresses and springback - the tendency of the material to return to its original shape after bending.
2. Part Tolerances - In general, the amount of information required is much smaller if the part tolerance is larger. I therefore assume that tighter part tolerances create more complex die designs.
3. Depth of Draw - The greater the part depth, the greater the likelihood of forming problems such as tearing and wrinkling. I used design axioms in Suh et. al. (1990) to evaluate the challenges associated with increasing part depth.
4. Die design: Sharp corners, deep draw depth and large radii create challenges for die manufacturing. For each part, interviews were conducted to evaluate the manufacturing complexity associated with the design, such as the stress-strain ratio and challenging design features.

Part Interconnectedness

If two parts can be changed in order to meet their functional requirements without affecting each other then they are independent (Suh et al., 1990). In order to evaluate part interconnectedness, I focused on the extent to which the information required to complete each part depended on other parts, using design axioms in Suh et. al. (1990), as well as in Ulrich and Eppinger (1998). For example, if a panel required only that its straight edge fit against another straight edge in a second part, there is little information required from the other part in order to fit the two together. This is known as a clean interface. In contrast, if two parts are required to fit at multiple points, in a more complex shape, then they require more communication when each part is changed. I assume that such parts are more interconnected.

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III. Sourcing By Design: Product Architecture and the Supply Chain[9]

1. Introduction

This paper focuses on two choice variables for manufacturing firms. The first is the choice between internal production and market purchase of components - the make/buy decision. The second choice for the firm is a product strategy, which has two main elements: product positioning and product architecture. Product positioning is the profile of the target customers and the desired product attributes for a particular market segment. In this paper, we take product positioning as given, and focus on *product architecture* as a choice variable for the firm. Product architecture is the layout of the components of a system to meet the performance determined by the product positioning. Product architectures can range from modular, or easily decomposable, designs to highly complex, or interconnected designs, which are difficult to decompose into standard parts. We argue that product architecture and firm structure are interdependent and interact with each other in determining the transaction costs faced by the firm (such as coordination costs among firms). This suggests that firms should focus on both structure and product architecture in order to optimize over all costs.

This work builds on past efforts to capture the role of asset specificity in the vertical integration decision in the firm. The usual model of firm structure takes asset specificity as exogenous, focusing on structure as determined by specificity. Our formal analysis begins with a model of the relationship between architectural complexity and sourcing. Using product *architectural complexity* as a proxy for asset specificity, we relax the exogeneity assumption and treat specificity as jointly endogenous with firm structure. In particular, we hypothesize that architectural complexity and sourcing are complements: that vertical integration is more valuable when architectural complexity is high. Thus, all else being equal, firms exhibiting high architectural complexity and a high degree of vertical

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[9] Co-Authored with Steven D. Eppinger

integration as well as firms exhibiting modularity and reliance on suppliers should outperform firms which have either architectural complexity and outsourcing or modularity and vertical integration by quality-based measures such as system reliability.

In this paper, we use data about automobile systems development to explore the link between product architecture and vertical integration decisions. There has been much research into product architecture and into the make/buy decision in the auto industry, yet to the best of our knowledge these decisions have never been studied jointly. We use an original dataset which includes not only the two simultaneous choices of vertical integration (in-house production) and architectural complexity but also exogenous variables, which should affect only one of the two choices directly. Our model provides evidence of such complementarity between product architecture and vertical integration, as well as evidence of clustering within the auto industry around high performance combinations.

We are motivated by the implications that follow if architectural complexity and vertical integration are interrelated. For example, a product designer may anticipate in-house production of a system and increase design complexity of the system, given his expectation that system development will be controlled by an internal group. An increase in complexity in the design phase, optimized anticipating in-house production, may lead to increases in both architectural complexity and sourcing. That is, increasing design complexity further increases the coordination costs faced by the firm in potential outsourcing decisions, increasing the likelihood of in-house production. After several generations of in-house production, design complexity may be increased to reflect the improved skill base within the firm. In this case, a model measuring only architectural complexity on vertical integration, rather than the two decisions simultaneously, would be upwardly biased in its estimate of the relationship between architecture and sourcing. Our analysis highlights how the relationship between product architecture and sourcing might affect the conclusions that can be drawn from earlier studies and allows for a better understanding of the interaction between these two decisions.

The remainder of this paper is divided into six sections. We first review the literature on product architecture and make/buy in Section 2. We then propose a conceptual framework for analyzing the relationship between product architecture and firm structure in Section 3. Section 4 contains the statistical evidence linking choices about make/buy to product architecture differences. We present summary data on the auto systems analyzed in our dataset. The data include measures of desired performance, platform requirements and union agreements. We present evidence of complementarity between architectural complexity and vertical integration. Section 5 presents a formal model of firm performance implied by complementarity between the architectural complexity and integration decisions. We present evidence of the variety of architecture and sourcing strategies observed in the industry, and examine these practices with respect to system performance. The paper concludes with a discussion about the implications of these findings for practice and for further research.

2. Motivation and Related Literature

This research builds on literature from several fields of study. The make/buy decision has been addressed by both economists and management scientists. The importance of product architecture 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 architectural complexity and firm structure. We begin with a review of the economic framework posed by transaction cost theory and incomplete contracting 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 architectural complexity and vertical integration.

2.1 Economic Theories of the Firm

In economics, firm-level activities are modeled as contracts (Jensen and Meckling, 1976). The decision to make or to buy a part depends on the cost associated with writing and monitoring a contract between the firm and an outside supplier - the costs associated with the transaction.[10] Transaction cost theory suggests three main reasons why it is difficult to write contracts. 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, writing and monitoring such a contract would be prohibitively expensive (Williamson, 1979). This means that the parties will write contracts that are incomplete. That is, the contracts do not anticipate and cover all possible outcomes. This imposes additional costs on the parties. They may have to renegotiate the agreement should an unforeseen event occur, and this can be time consuming and therefore costly. 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 (Grossman & Hart, 1986, Hart & Moore, 1990, Hart, 1995). This literature predicts integration when transaction costs are high. One kind of transaction cost which might be particularly salient is coordination cost.

Klein, Crawford and Alchian (1978) argue that coordination problems arising from relationship-specific investments will be less severe if the transaction is internalized. The firm (vertical integration) is distinct from a market entity in that disputes within the firm can be resolved without legal action or outside monitoring. That is, given that contracts are incomplete, unforeseen development problems can occur. The firm is able to resolve these unforeseen problems internally and thus it is able to capture the full gains from its investment under all possible outcomes. From this notion, Klein, Crawford and Alchian

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[10] To date, the empirical testing with regard to theories of the firm in economics has been restricted to testing of transaction costs. While there are more sophisticated theories of firm structure such as the property rights approach (Grossman and Hart, 1986) or the firm as an incentive system (Milgrom & Holmstrom, 1994), we focus on transaction cost theory in order to motivate our discussion of the existing empirical literature.

conclude that vertical integration is the likely firm structure for transactions in which asset specific investment is important.

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 how transaction costs vary under different firm structures. Monteverde and Teece (1982) analyze a dataset comprised of 133 component sourcing decisions at Ford and GM 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 non-appropriability of technical knowledge, leading to profits which the firm can capture only if it vertically integrates.

Masten, Meehan and Snyder (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, and Masten, Meehan and Snyder 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 modular design that reduces coordination costs. Alternatively, many hours could be spent on a highly complex design to optimize product performance, resulting in a part that has the predicted high information requirements. Therefore, engineering hours is not a direct measure of the cost of the transaction in the market. In this paper we argue that a better measure of transaction costs can be developed using ideas from the literature on product architecture. In particular we propose that transaction costs are best represented as a function of *product architectural complexity,* discussed in detail below.

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 tradeoff is exemplified by the decision between purchasing standard parts and developing custom components in house. Standard products - if they have clean, or well understood, interfaces - can be outsourced more easily, but may present tradeoffs in terms of performance and cost over custom parts development (Ulrich and Ellison, forthcoming).

Baldwin and Clark (1998) 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 US 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.

Product architectural complexity can be used to interpret the Clark and Fujimoto results differently. 92% of the vehicles studied in Japan were mini to small, as compared to the US, where 83% were large. Larger, more expensive vehicles have a wider range of choices in performance goals, and often necessitate more integral designs than smaller, cheaper cars.[11] The prevalence of black-box engineering in Japan could be attributed to the simplicity of the vehicles in the segments examined; small vehicles may tend to be more modular, and therefore easier to develop rapidly with outside suppliers. The uniqueness of the part may be less important than its complexity in affecting development time.

The concept of product architectural complexity used widely in the system engineering literature (Suh, 1990; Alexander, 1964) provides the opportunity to enrich the measurement of coordination costs. An outsourcing decision can result in different potential dependencies on suppliers based on the amount of information that must be communicated in order to complete vehicle development. If the component or components can be designed with a well-defined interface with the rest of the system, the product may not require much communication with suppliers.

For example, the decision whether or not to outsource components of an automatic transmission to a supplier, can result in either relatively minor or quite extreme coordination problems depending upon the complexity of the product architecture chosen.

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[11] A small vehicle may necessitate a more integral design as a result of the need to conserve on mass and size. However, the limitations in performance options in smaller vehicles necessarily simplify the requirements for all but the body system.

A transmission using a planetary-axis gear set can be readily decomposed so that the gear set can be developed separately from the rest of the system and outsourced. On the other hand, a transmission using a parallel-axis gear set is highly interconnected. A supplier developing a parallel-axis gear set requires close interaction with the transmission manufacturer, and any supplier problems can affect more of the system development because the outsourced components interact with the rest of the transmission system at many points. Ulrich and Eppinger (1995) suggest that a group of components should be assigned to a single individual or team if the design requires extensive coordination of interactions among components within the system. For this reason, teams relying on outside suppliers may opt for a modular architecture.

Fine and Whitney (1996) summarize product development as the ability to write competent specifications for components and systems and to be sure the specifications are realized. They list three distinct outsourcing motivations: development capacity, manufacturing competitiveness, and product technology. The decision to outsource depends on whether the firms seeks knowledge or capacity and whether the product is readily decomposable from rest of the system. In our transmission example, many companies with different information-processing capabilities but choosing the simpler architecture (planetary-axis) are able to outsource gear sets 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 which repeatedly relies on an outside supplier to develop a system which is highly integral 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.

3. Conceptual Framework

The analysis in this paper is based on a study of product architecture and sourcing in the auto industry. Our newly developed dataset covers components in eight vehicles over five consecutive 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. 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.

Our research builds upon the work of the above-mentioned authors. The dataset analyzed here provides the opportunity to explore these ideas empirically and to overcome some of the shortcomings of the earlier work. In particular, we highlight three aspects of our study design:

3.1 Unit of Analysis

The unit of analysis in our empirical study is the automotive system. The reality for most systems is that some of the components are low in technical complexity, while others may be much more complex. Similarly, some components within the system may be highly interrelated, while others are independent. The sourcing decision, then, requires careful evaluation of the tradeoffs associated with the system as a whole, as well as the part-by-part decision. It is for this reason that we choose to use system, rather than component-based, measures of product architecture and sourcing. 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 architectural complexity, sourcing and quality.[12] To accurately represent the sourcing and architectural complexity of each system, we collected detailed data about the many components comprising each system.

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

We collected data focused on the same components in a single vehicle segment in the auto industry in order to remove the possible measurement problems caused by a dataset which combines information from different vehicle types, such as that of Clark and Fujimoto (1991), or from different component types, such as Masten, Meehan and Snyder (1989). In particular, we studied luxury performance cars, defined by *Consumer Reports* as vehicles 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 this segment represents the flagship vehicles for the auto companies, we expect that this segment provides the most powerful and comparable test of the possibilities available to auto firms in both product architecture and sourcing. A review of the data (see Table 3.4.1) indicates that there is a wide range in product architectural complexity choices and sourcing choices, as well as in system performance. The wide range of sourcing and architectural complexity possibilities indicate that there are many choices in design and production available to firms within the luxury performance segment.

3.2 Timing

Relative to both the product architecture and sourcing decisions, market-positioning tends to be much more historical, long term, and based on reputation. We thereby treat the market-positioning decision as fixed, focusing exclusively on product architectural complexity and sourcing decisions. Since the choice of product positioning exceeds the timespan of the sourcing decision, we also assume the product architectural complexity measure is fixed over the life of the vehicle model. This approach is consistent with the marketing literature on product placement (Urban & Hauser, 1993).

3.3 Product Architecture as a Measure of Transaction Costs

Without a direct measure of the impact of product architectural complexity on coordination costs, we choose to estimate the impact of increasing complexity on cost of a design change. We treat cost of change as an increasing function of complexity because the more interconnected a design is, the more closely coupled are its elements. Therefore, whenever change occurs in a part, this change affects many more aspects of the product. This requires coordination in design to integrate all of the elements, as well as potentially adjusting to the space constraints imposed by the physical proximity of all the elements. If these are very tightly connected, any change may prove very difficult, and thus costly, in hours.

We hypothesize that *increasing complexity in product architecture will drive vertical integration*, in that a firm seeking to minimize the coordination costs associated with developing a complex part will internalize production. Two forces suggest complementarity between product architectural complexity and sourcing.[13] The first is the aforementioned reduction in coordination cost associated with concentrating complex development within the firm. The second is the impact of outsourcing more modular systems on the holdup problem. Our view is that, while contracts remain incomplete, it becomes easier for the firm to switch between suppliers if interfaces are well-defined.[14] The firm can use this reduced dependence on the supplier in question to improve its bargaining position and to secure more of the project surplus.[15] Thus modularity increases the gains to outsourcing. The interaction between these choices suggests a model where architecture and sourcing are chosen in tandem, even through sourcing follows design chronologically in most automotive companies. We test for the relationship between architectural complexity and sourcing empirically in Section 4.

4. Relationship Between Product Architecture and Sourcing

In this section, we explore the relationship between product architecture and sourcing. We begin by describing the factors which directly affect the costs and benefits of

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[13] That a move from 0-1 in architectural complexity increases the returns to a move from 0-1 in integration.

[14] This is not the same as the standard versus custom parts argument presented in Baldwin and Clark (1998). For example, a custom part may have a well-defined interface between a firm and supplier, and can be developed relatively easily. Our argument concerns the definition of the interface between the parties required for system development.

architectural complexity and sourcing. We use a two-equation simultaneous equation model with Sourcing and Architectural Complexity as the two dependent variables. The hypothesized relationship between product architecture and sourcing is illustrated by Figure 3.4.1. The independent variables, or outside factors affecting product architectural complexity (ARCH), are performance goals (PERF), major change (MAJ), worker skills (SKLZ), technology breaks (TECH), sunk cost (SNK) and platform requirements (PLAT). The independent variables affecting sourcing (SRCE) 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 3.4.1.

The dependent variable sourcing (SRCE), is the percentage of the system produced in-house, with 1 indicating in-house production of all components. [16] For each component, system, vehicle model, and time period, we have collected data on the make/ buy decision outcome. All component sourcing decisions are equally weighted 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 one (in-house production), with a mean of .37 and a standard deviation of .36, as shown in Table 3.4.1.

The measures of product architectural complexity used in this paper are based on detailed system design and manufacturing data. For each system, we estimate product architecture on a spectrum from 0 to 1 (modular to high architectural complexity) as an

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[15] This view is consistent with the result in Hart & Moore (1990) that complementary assets should be held together.

[16] 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 Section 6.

unweighted average of characteristics of design complexity.[17] 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, architectural complexity in the suspension system is represented 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. These measures are presented in Appendix 3A. This measure is then used for all components in the system. The dependent variable product architectural complexity (ARCH) measures the complexity of the system, with a score of 1 indicating high system complexity. As shown in Table 3.4.1, product architectural complexity spanned the full range from 0 (fully modular) to .99 (high architectural complexity), with a mean of .42 and a standard deviation of .27.

PERF is a (0-1) measure which proxies for desired performance at the system level. Certain performance goals necessitate integral architectural choices in systems. (Ulrich, 1994). For example, a result of designing to meet high top-speed capability is a body system consisting of tightly interconnected parts.[18] In our dataset, performance goals were provided by vehicle product managers, on a 0-10 scale, with 10 indicating a high value, i.e., the vehicle was defined by performance in the system. We expect systems for which performance goals are very high are likely to be associated with integral product architectures and hence, we expect a positive relationship between PERF and ARCH.

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 range from every four years to every seven years (Clark & Fujimoto, 1989). The company has more opportunity to change architectural complexity in major changes, and we expect that in performance

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[17] For each system, measures of complexity were chosen on the basis of system engineering principles. Final "key characteristics" were selected by company experts as most representative of overall system product architecture. Clearly, there are interactions across systems as well. For example, if a body design is highly integral, the specifications for an outsourced door will influence the dashboard and the firewall specifications at more critical points than if the design were more modular. In order to relate product architecture to component data on sourcing, we believe system-level measures best capture the coordination issues.

vehicles these changes should involve greater performance, and therefore greater architectural complexity. We expect a positive relationship between MAJ and ARCH.

SKLZ reflects 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. A value of 1 indicates the presence of skill limitations as a factor in system design, and we expect a negative relationship between SKLZ and ARCH. The SKLZ measure was defined by vehicle product managers, who were asked if absence of worker skills played a role in design considerations for each system

TECH, the variable reflecting the state of technology, is a dummy which 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 thus expect a negative relationship between TECH and ARCH.

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 which was built on the same platform. For this reason, we hypothesize that PLAT will have a negative affect on ARCH. With regard to sourcing, platform requirements could

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

support in-house production through economies of scale achieved through parts sharing. For this reason, we hypothesize a positive relationship between PLAT and SRCE.[19]

SNK is a dummy variable reflecting existing sunk cost/plant investment. Systems are often designed around sunk investment in process equipment in the plants. This may constrain design to a more complex company-specific process (as in the case of Honda and parallel-axis gear sets in transmission) or to a simpler process (such as GM with engine blocks). Thus, we expect SNK to have a significant effect on ARCH but make no prediction on the direction of the relationship. With regard to sourcing, a system may be built in house due to existing plant investment. On the other hand, systems are often outsourced due to existing in-plant variation problems in manufacturing. For this reason, we also test the significance of the relationship between SNK and SRCE, but we make no prediction on the direction of the relationship.

CAP is a dummy variable indicating limited plant production capacity or capability. 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 SRCE.

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 luxury performance volume is much smaller than BMW's. BMW may be able to command a larger, not smaller, ordering capacity with suppliers due to 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 SRCE.

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

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 due to the extreme cost and risks associated with union renegotiation. For this reason we expect a positive relationship between UNION and SRCE.

4.1 The Statistical Model

Our principal concern in this paper is to study the relationship between product architecture and sourcing. The preceding discussion suggests that some form of integration is likely to be chosen as part complexity increases. However, we have argued that product architecture and sourcing are coupled. Econometrically, this suggests a model where product architecture and sourcing are simultaneously determined, so that our model should treat these two variables as jointly endogenous (Hausman, 1983). That is, architectural complexity (ARCH) may be related to sourcing (SRCE) in the following linear regression:

$$(1.1)\ \text{ARCH} = \beta_0 + \beta_1\text{SRCE} + \gamma Z + \varepsilon_1$$

where Z is a vector of other variables thought to affect product architecture,
and sourcing may be related to product architecture as

$$(1.2)\ \text{SRCE} = \alpha_0 + \alpha_1\text{ARCH} + \delta W + \varepsilon_2$$

where W is a vector of other factors thought to affect sourcing.

If one were to run only the regression (1.1), using a method such as ordinary least squares (OLS), the resulting measure for β_1 would be biased and inconsistent, due to the presence of ε_2 in the variable SRCE. Again, this is because there may be unobserved factors in sourcing which are correlated with the product architecture decision. Hausman

(1983) has shown that using an instrumental variables approach always leads to consistent estimation for an identified model. This is the approach taken in this paper. In order to test for the relationship between product architectural complexity and sourcing, we estimate the following model:

(2.1) $\text{ARCH} = \beta_{1o} + \beta_{11}\,\text{PERF} + \beta_{12}\text{MAJ} + \beta_{14}\text{SKLZ} + \beta_{15}\text{TECH}$

$+\beta_{16}\text{SNK} + \beta_{17}\text{PLAT} + \gamma_1\text{SRCE} + \varepsilon_1$[20]

(2.2) $\text{SRCE} = \beta_{2o} + \beta_{23}\text{CAP} + \beta_{26}\text{SNK} + \beta_{27}\text{VOL} + \beta_{28}\text{UNION} + \beta_{29}\text{PLAT}$

$\gamma_2\text{ARCH} + \varepsilon_2$[21]

A consistent estimator of the system described by (2.1) and (2.2) is optimal instrumental variables, instrumenting for ARCH in (2.2) and SRCE in (2.1) with the instruments Z.[22] 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, we assume that performance goals, major changes, worker skills, and technology breaks are uncorrelated with unobserved factors in sourcing, i.e. ε_2, but are correlated with sourcing decisions. Similarly, we assume that capacity limitations, company volume, and union are uncorrelated with unexplained variations in product architectural complexity, but are correlated with architectural complexity decisions. Instrumental Variables methods allow for unbiased estimates of our dependent variables. 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.

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[20] Plus year, company and system dummies.

[21] Plus year, company and system dummies.

[22] Identification conditions are reviewed in Appendix 3B.

In order to test the effect of ARCH on SRCE (equation 2.2), we first estimate equation (2.1) and formally validate our proposed model using the Hausman specification test (Hausman and Wise, 1978) as follows. We believe that the ARCH 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 ARCH directly as a function of all the instruments, generating a predicted value ARCHhat.[23] As the dependent variables are (0-1) binary measures, we first ran a probit regression of all the instruments on ARCH to obtain ARCHhat. The results of this regression are presented in Table 3.4.2. The difference between the observed values ARCH and the new values ARCHhat is our estimate of ε_1, or the unobserved factors in ARCH, which we label "Vhat". We then ran an ordered probit regression of equation (2.2), with the addition of Vhat as a variable. If in fact, we have removed the relationship of SRCE on ARCH, there should be no relationship between ε_1 and SRCE.[24] That is, there should be no correlation between unobserved variables in ARCH and the sourcing decision. Table 3.4.3 presents the results of the Hausman Specification Test.

The relationship between Vhat and SRCE is insignificant, at a 60% level of confidence.[25] As there is no relationship between our estimated error and SRCE, this allows us to measure the effect of ARCH on SRCE using an ordered probit regression.

In summary, our model recognizes the econometric implications of the coupling between the architecture and sourcing decisions. Our study design permits us to measure the impact of architectural complexity on sourcing, and we have formally validated our methodology using a test of the simultaneity between the architecture and sourcing

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[23] This is the same as running the reduced form regression ARCH = $Z\Pi + V$. See Hausman (1983).

[24] This is equivalent to running SRCE = $x\delta + \gamma 1 \text{ARCH} + \gamma 2 \text{vhat}$. H_0: $\gamma 2=0$. See Hausman (1983).

[25] 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.

decisions. Again, consistent with system engineering and transaction cost arguments, we predict that ARCH will have a positive affect on SRCE ($\gamma_2>0$). No predictions are made concerning company-specific effects.

4.2 The Effects of Architectural Complexity on Sourcing

Table 4 presents the results of an ordered probit regression of equation (2.2). We tested for the effect of years on sourcing, and found that year dummies are not significant, and thus dropped year dummies from our estimation.[26] 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 dummies, volume dummies and capacity limitations did not play a significant role in the sourcing decision.

ARCH, our proxy for asset specificity, 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 architectural complexity is correlated with an increase in in-house production. This is consistent with our prediction that more complex designs pose a greater coordination problem, and thus are better managed by concentrating development within the firm.

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 US auto industry, where union agreements cover all components currently manufactured within a US plant. In order to outsource a component, it is necessary to renegotiate the union agreement, a prospect which is costly at best, and at worst, can result in a debilitating strike. As a result, US firms face a far greater penalty in attempting to outsource existing components, and are thus more likely to build even modular systems in

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[26] In this test, we test the null that all year dummy coefficients are equal to zero. At F=.76, P > F = .60, so

house. We believe this relationship, between UNION and SRCE, may be the source of the significance found in the GM dummy in the Monteverde and Teece study, reflecting the fact that in 1976, GM had a great many more plants and components covered by union agreements than Ford, the other company in the study.

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. Again, this is because the firm would face additional monitoring costs by outsourcing and allowing suppliers to build similar economies of scale. It may also be the case that the platform requirement requires more modular designs overall, 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 due to existing in-plant variation.

In summary, the predictions of our model - that ARCH, 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 architectural complexity and vertical integration are complementary, suggests a model of firm performance as a function of the interaction of these two organizational design choices. Athey & Stern (1998) provide a formal econometric model of analyzing complementary organizational design practices, and our model follows from their general framework.[27]

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we are unable to reject the null, and thus are able to drop dummy variables.

[27] Athey and Stern (1998) point out that there may be unobserved factors in the organizational choice equations which affect the performance results. With this in mind, our regressions results, although qualitatively similar to our formal model predictions, are not complete.

Complementarity between architectural complexity and sourcing implies that vertical integration is more valuable when architectural complexity is high. In order to summarize our performance results, we group these choices into 2 categories, low and high, where $0 \leq r_i \leq$system median is "low" and system median$\leq r_i \leq$ 1.0 is "high", resulting in four possible combinations: y^j = {low, low}, {low, high}, {high, low}, {high, high}. Our hypothesis is that complex-in-house (y^1) and modular-outsourced (y^4) will be positively correlated with quality performance. Obviously, performance is affected by a variety of other factors in addition to architecture and sourcing decisions. With this in mind, we compare the results of different architectural complexity and sourcing combinations to observed performance outcomes in a descriptive regression.

As in our model design, we treat performance goals and product placement as determined from customer requirements, we measure system performance at the system level using customer evaluations of quality. 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 3.4.1, all five possible scores were reported for all of the systems in the study. Across all the systems, mean quality performance also fit our model predictions. Modular-outsourced approaches had the highest mean quality of 3.7 out of 5. Complex-in-house had the next highest mean quality, at 3.2. Complex-outsourced had a mean quality of 3.1. Modular-in-house had a mean quality of 2.5. Following from our structural model in Figure 1, we specify firm quality performance (Q) in the following regression:

$$\text{(3)}\quad Q = \Sigma\beta_{ij}y^j + \beta_3 ARCH*MAJ + \beta_4 ARCH*SNK \;\; \beta_5 ARCH*PLAT + \beta_6 SRCE*SNK + \beta_7 SRCE*UNION + \beta_3 SRCE*PLAT + \varepsilon$$

The results of this regression are presented in Table 3.5.1. We find that the quality returns to a modular-outsourced strategy and a complex-outsourced strategy far exceed the returns to a modular-in-house strategy, at a 95% level of certainty. Complex-in-house approaches weakly outperformed modular-inhouse approaches. While these results are supportive of our hypothesis are consistent with our hypothesis that the greatest gains in quality performance should be attained with modular-outsourced and complex-in-house strategies, we are unable to draw further statistical conclusions with regard to determinants of firm performance. However, in terms of the particular systems, we present informal observations which support our hypothesis.

In the suspension system, architectural complexity (ARCH) ranged from nearly modular (.11) to the highest possible score for complexity (.99). Defining ARCH above .5 as complex (below .5 as modular) and sourcing (SRCE) above .5 in-house as in-house (below .5 as outsourced), the vehicles in the study exhibited suspension choices in all four categories (complex-in-house, complex-outsourced, modular-in-house, modular-outsourced). The top performer in the category, with a reliability score of 5, featured a modular-outsourced design. This is consistent with our view that products designed to be modular can be more effectively outsourced. The worst performer in the category, with a score of 5, featured a complex-outsourced design. This result is consistent with the ideas that products which are sufficiently complex cannot be easily decomposed and outsourced.

In the body system, the best performers, with reliability scores of 5 were complex-in-house and modular-outsourced. The worst performers, with reliability scores of 1, were modular-in-house and complex-outsourced. Again, this is consistent with our hypothesized relationship between architecture and sourcing.

The transmission system featured a range of architectural complexity choices from a low of .25 to a high of .875. Sourcing ranged from completely outsourced to completely in house. The top performers in the category, with reliability scores of 5, were modular-outsourced and complex-outsourced. The worst performers, with reliability scores of 2, were modular-in-house. The performance of the modular-outsourced and modular-in-house vehicles are consistent with our predictions.

The performance of the vehicle featuring the complex architecture with in-house production of transmissions, raises a measurement issue we encountered with our dataset. With regard to transmissions, the vehicle in question ranked as high complexity as a system, and the company in question produced the most integral components of the system in house, outsourcing only the most simple components. On a content basis, their in-house production was not low, and in fact their performance can be seen as consistent with our hypothesis that complex-inhouse ought to perform highly. However, any attempts 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 hypothesized relationship between architecture and sourcing, we believe any such corrections would strengthen our results.

In the engine system, architectural complexity ranged from 0-.71. Sourcing ranged from .27 to 1. All companies in the study manufacture the "big 5" integral components - cylinder head, engine block, crankshaft, camshaft, and intake manifold, and the variation in sourcing centered around the more potentially decomposable components such as pistons. The top performers were complex-outsourced, again, due to the equal weighting of component sourcing. The worst performer was modular-in-house.

In the brake system, architectural complexity choice ranged from completely modular (a score of 0) to quite complex (a score of .864). However, all but one of the companies in the study outsource brakes as a complete system. The lack of variance in sourcing choices limits our ability to interpret the quality reviews with respect to our hypothesized relationship between architecture and sourcing. The top performers were both complex-outsourced and modular-outsourced. The worst performer was modular-in-house.

In the electrical system, both architectural complexity and sourcing ranged from 0-1. The worst performer featured a modular-in-house approach. The top performer, again, was modular-outsourced.

The steering system results also reflect another measurement issue we encountered in our dataset. The best performer, with a reliability score of 5, was a complex-outsourced vehicle. The worst performers were modular-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.[28]

However, in the complex-outsourced steering system, as well as in many of the systems in the study, all Japanese companies who outsourced individual parts concentrated the more complex of those parts in keiretsu suppliers, and outsourced more modular parts to financially separate suppliers. In contrast, most US 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) 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 is 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 in order 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 performance suggests that there is not one way to optimally configure the firm or the product, but rather that multiple optima exist. This

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

suggests that companies should not necessarily seek to emulate the "Toyota way" of outsourcing or a BMW-style product development. Rather, our research suggests that a company which optimizes over the requirements of its product architecture and the capacity of its supply chain will outperform one which focuses only on firm structure or product characteristics.

6. Discussion

In summary, our model provides evidence of complementarity between product architectural complexity and vertical integration, as well as evidence of clustering within the auto industry around high performance combinations of the two choice variables. This has implications for optimal incentive structures within firms, as well as for interpreting the performance outcomes of firms.

The results of this model strongly support the strategic importance of the architectural decision in the make/buy process. Given our observation that there are observed quality benefits to concentrating production of complex systems in-house and to outsourcing modular systems, efficiency arguments suggest that profit-maximizing firms should only operate according to these approaches. This raises the question of why it is that we ever observe firms outsourcing complex systems or producing modular systems in-house. We believe that this outcome is a result of the chronological and organizational separation of these decisions in automotive companies. Product architecture is typically determined by product design engineers, and the make/buy decision is typically made by purchasing agents, who may not be engineers. While these groups may interact, they do not make these decisions jointly. The results of our study suggest that greater coordination of these functions within the product development process could lead to improvements in firm performance.

This paper also raises significant 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 in order 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 alternate practices can create very different information structures, with significant 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 theoretical and empirical work on make/buy. Ulrich and Ellison (1998) propose some alternative sourcing measures in an empirical study of bicycle sourcing. Novak (1999) uses an approach based on the property-rights view in incomplete contracting (Grossman & Hart, 1986; Hart & Moore, 1990; Hart, 1995) to explore this question further in a theoretical model of ownership structures. In addition to the need to enrich the concept of the make/buy decision, we believe that our results also raise issues with regard to the information structure of firms.

The results of our system level analysis suggest that the quality benefits to designing modular systems for outsourcing (a modular-outsourced strategy), as well as the quality penalties for attempting to outsource integral systems (a complex-outsourced strategy) outweighed the quality benefits of in-house production of modular systems (modular-in-house) as well as in-house production of complex systems (complex-in-house). This suggests that a complex design is still difficult to execute well within the firm, and that developing a modular part within the firm does not necessarily improve its quality over outsourcing such a part.

In his 1988 review of the state 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 architectural complexity and sourcing, through which to further explore this issue.

System	Mean ARCH	Std Dev ARCH	Mean SRCE	Std Dev SRCE	Range in Quality*
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)

*Quality is defined according to Consumer Reports Reliability Reviews, which are rated per vehicle system.
A score of 5 corresponds to fewer than 2% problems per system, the top C.R. score.
A score of 4 corresponds to 2% to 5% problems per system.
A score of 3 corresponds to 5% to 9.3% problems per system.
A score of 2 corresponds to 9.3% to 14.8% problems per system.
A score of 1 corresponds to more than 14.8% problems per system.

Table 3.4.1 Summary Data on Automotive Systems

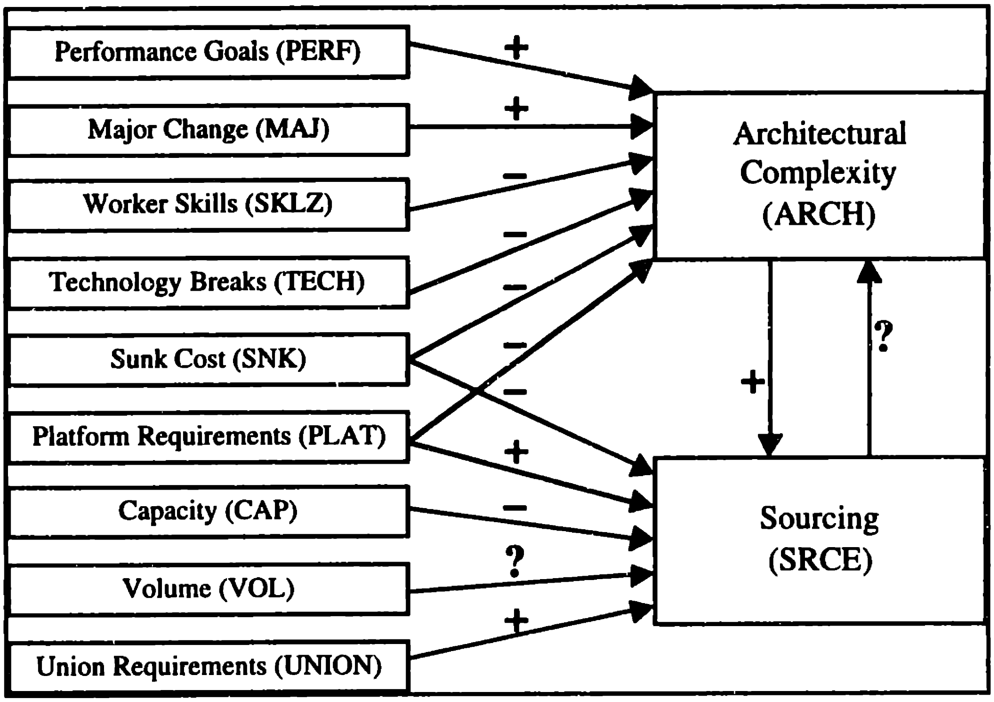

Figure 3.4.1 Hypothesized Relationships

Dependent Variable	Coefficient	Std. Error	z	p>lzl
ARCH				
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 .01 level; **=significant at the .05 level
N=134, Adjusted R^2=.30
Chi^2=34.95

Table 3.4.2 Regression Results for Architectural Complexity

Dependent Variable	Coefficient	Std. Error	z	p>lzl
SRCE				
Independent Variables				
ARCH	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 .01 level, **=significant at the .05 level
N= 134, Pseudo R^2=.37

Table 3.4.3 Hausman Specification Test

Dependent Varial	Coefficien	Std. Error	z	p>|z|
OSRCE				
ARCH	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	**-1.922	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 .01 level, **=significant at the .05 level
N=134, Adjusted R^2=.39
Chi^2=113.28

Table 3.4.4 Regression Results for Sourcing

Dependent Variable	Coefficient	Std. Error	z	p>|z|
QUAL				
Arch-Srce Approach				
COMP-IN	0.49	0.37	1.36	0.17
COMP-OUT	0.85	0.38	*2.21	0.03
MOD-OUT	0.92	0.38	*2.44	0.02
System Interactions				
ARCH*MAJ	0.78	0.54	1.44	0.15
ARCH*PLAT	-0.41	0.59	-0.71	0.48
ARCH*SNK	-0.63	0.78	-0.81	0.42
SRCE*SNK	-0.04	0.68	-0.07	0.95
SRCE*UNION	-0.03	0.5	-0.07	0.95
SRCE*PLAT	-0.05	0.46	-0.11	0.92
System Dummy Variables				
Suspension	-0.34	0.38	-0.9	0.37
Transmission	-0.22	0.38	-0.57	0.57
Engine	-0.2	0.41	-0.49	0.63
Steering	-0.41	0.4	-1.3	0.3
Body	-1.3	0.42	*-3.13	0

*Significant at the .05 level
N=112, Pseudo R^2=.17
Chi^2=39.04

Table 3.5.1 Regression Results for Quality

Appendix 3A. Architectural Complexity Measures

System	Measures Used
Suspension	newness + moving parts + active/passive
Brakes	#channels + # solenoids + traction controller + ABS (electrical vs mechanically-based)
Transmission	drive (RWD/FWD) + gearsets + traction control + automatic
Engine	electronic control + traction control + transverse axis + cam configuration + valve lift + metal
Steering	adjustability + knucle attachment + airbag integration
Body	parts body side outer + parts inner + # thicknesses + type of joints + # hits most complex part
Electrical	#multiplexes + wiring configuration + system integration (controls)

Appendix 3B. Conditions for Identification and Estimation

The standard rank condition, necessary and sufficient for identification, is satisfied if rank $\phi[\beta\Gamma] \geq M-1$ where M = the number of restrictions. Rank is satisfied for equation 1.3 and 2.3 if rk $[0\ {-\beta_2}] \geq 1$, rk $[-\beta_1\ 0] \geq 1$, respectively. The order condition is satisfied if at least two elements of Z_2 and Z_1 are nonzero. Joint endogeneity is eliminated from the model by the reduced form transformation, where each dependent variable is rewritten only as a function of exogenous variables. We rewrite equations (1.3) and (2.3) as:

(1.4) $Y_1 = \Delta\ [\beta_{oo} + \beta_{1o} + \beta_{11}x_1 + \beta_{12}x_2 + \beta_{23}x_{3+}\ \beta_{14}x_4 + \beta_{15}x_5 + (\beta_{16} - \gamma_{12}\beta_{26})x_6\beta_{27}x_7 + \beta_{28}x_8 + \beta_{29}x_9 + \beta_{1,10}x_{10} + \beta_{2,11}x_{11} + (\varepsilon_1 - \gamma_{12}\varepsilon_2)] = Z\Pi_1 + V_1$[29]

(2.4) $Y_2 = \Delta\ [\beta_{oo} + \beta_{1o} + \beta_{11}x_1 + \beta_{12}x_2 + \beta_{23}x_3 + \beta_{14}x_4 + \beta_{15}x_5 + (\beta_{26} - \gamma_{21}\beta_{16})x_6 + \beta_{27}x_7 + \beta_{28}x_8 + \beta_{29}x_9 + \beta_{1,10}x_{10} + \beta_{2,11}x_{11} + (\varepsilon_2 - \gamma_{21}\varepsilon_1)] = Z\Pi_2 + V_2$[30]

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[29] $\Delta = 1/1-\gamma_{21}$, Z = [x1-x11]

[30] $\Delta = 1/1-\gamma_{12}$

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