

The Impact of Technological Interdependency on Contracting Complementarities: Evidence from Automobile Product Development^{*}

by

Sharon Novak
Kellogg School of Management
s-novak@kellogg.northwestern.edu

Scott Stern
Kellogg School of Management, Brookings and NBER
s-stern2@northwestern.edu

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This paper examines the impact of contracting complementarity across product development systems in the automobile industry. While most empirical research on contracting assumes that each governance choice is independent of each other, cross-system integration and incentive problems within product development suggest the potential for complementarities across contracting choices within the firm. This paper develops and implements an instrumental variables estimator which allows us to distinguish contracting complementarity from firm-level fixed effects in governance choice. Taking advantage of system-level determinants of vertical integration to calculate instruments for system-to-system contracting complementarity, we establish three findings. First, contracting choices are “clustered”: the probability of vertical integration for each automobile system increases in number of other systems that are vertically integrated. Second, instrumental variables and reduced-form estimates suggest that contracting complementarity, rather than unobserved firm-level factors, are the drivers of this correlation. Finally, the degree of correlation in governance is sensitive to the underlying contracting and technology environment, and contracting complementarity seems to be highest for those interactions where integration and coordination are most critical. While we interpret these findings cautiously, the results suggest that assuming away contracting complementarity may be problematic in contexts where coordination activities are both important and difficult to monitor.

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I. Introduction

The empirical drivers of vertical integration and firm boundaries have received considerable and well-deserved attention over the past decade. New product development stands as a central setting in which the role of contracting has been explored. This is not surprising, as product development choices reflect key features of the contracting literature, including the importance of non-contractible investment and the potential for renegotiation.

Both economists and product development researchers have contributed to this recent literature. Despite broad similarities, researchers from these two different fields have emphasized different aspects of the design process. For example, most economics research on vertical integration in manufacturing focuses on the determinants of vertical integration at the level of *transactions*. In the context of product development, this has placed emphasis on individual technical *components*, with a focus on how factors such as asset specificity or relative bargaining power drive the vertical integration decision at the most “micro” level of decision-making (Monteverde and Teece, 1983; Masten, 1984; Masten, Meehan and Snyder, 1991). In contrast, product development researchers have increasingly identified the *interaction among components* as perhaps the single most important “problem” in managing new product development (Eppinger, et al, 1993; Ulrich, 1995; Suh, 1999; Baldwin and Clark, 2000).

Consider the well-known case of failure involving Ford and Firestone. While both Ford and Firestone successfully completed the design and production responsibilities laid out in their contract, the parties were not able to effectively manage the interface between their responsibilities. At least in part, this coordination problem was exacerbated by the fact that Ford was unable to manage system-to-system coordination activities with Firestone as effectively as they might had tire design and supply been maintained in-house. While the safety hazard that resulted from this contracting problem is likely an extreme case (e.g., Firestone was forced into bankruptcy by the resulting liabilities), the Ford/Firestone case and other related cases highlight the key role of managing system interactions in determining performance. More specifically, an important economic implication of these rich descriptions is that non-contractibility and hard-to-observe effort provision are most critical at the level of *system* management rather than *component* management.

More than simply a theoretical concern, the product development literature holds important implications for measurement and theory testing in this area. Specifically, component-level analyses of vertical integration depend critically on independence between individual component decisions. To the extent that the drivers of vertical integration depend on the salience of difficult-to-monitor interactions among components, component-level analyses are potentially biased. Addressing such biases requires a shift in both the level of analysis (system rather than component) and the measures employed to capture variation in the microeconomic contracting environment (e.g., factors that may impact the contractibility of system-to-system interactions).

This paper examines interdependence among vertical integration decisions in the automobile industry. Specifically, we explore a detailed dataset of product development decision to test for the presence of *contracting complementarity* -- systematic relationships between individual vertical integration choices by a given firm. The potential for contracting complementarity arises from the tradeoff between effective cross-system integration and the provision of incentives that are the heart of the product development process.

In most cases, overall performance cannot be achieved simply by optimizing the performance of each component (or even each major system) but requires substantial investment in coordinating design and technology choices across systems. While some level of integration can be written into formal contracts, effective integration depends on subtle contingencies and hard-to-predict circumstances. For example, most systems are produced to a given range of specifications (e.g., the gear box for the transmission system should be 12cm wide plus or minus 2 cm). However, even if all systems are within range, minute differences in size (one system is to the low end of its range when the other is to the high end) can result in system-to-system failures, the precise source of which is difficult to verify. By its very nature, effective integration requires repeated disclosures of key technical details between system developers, and non-contractible investments in coordination and problem-solving. This non-contractibility of investment raises the possibility that ownership and control rights may be assigned in such a way as to shape the post-contracting incentives of both the firm and developers, trading off the benefits of integration with the potential for high-powered incentives through external supply contracts.

Indeed, by offering internal incentives and establishing internal procedures to ensure adequate investment in coordination activities, the management of system-to-system integration may be a key benefit to vertical integration. For example, even when the ability to write *ex ante*

contracts are identical for both in-house teams and external suppliers, the firm may not be able to commit to high-powered incentives for in-house teams since internal employees are both liquidity-constrained and can hold up the firm on future projects. Despite this loss in incentives for contractual performance, in-house teams may improve incentives for the *non-contractible* investments in integration that are central to system-to-system coordination. Moreover, these benefits to vertical integration for any one system may be higher when other systems are vertically integrated. For example, when the management of system-to-system interactions requires the disclosure of key technical details and strategic choices, trade secrecy concerns may limit the incentives of the firm to facilitate integration unless all development is in-house. As a result, the marginal returns to vertical integration for any one system increases in the extent of vertical integration of related systems, a condition which implies complementarity across the system-level contracting choices of the firm. As a result, even when contracting choices are *observed* at the system level, the economic drivers of contracting need to be *analyzed* at the system-to-system level, to account for potential contracting complementarity.

We explore these ideas using a detailed proprietary dataset covering luxury automobile models over a fifteen year period. For each model, we observe the both the degree of vertical integration and contracting environment for seven distinct systems in the automobile (e.g., the brake system, the seat system, the engine system, etc.). In contrast to most datasets (where data is collected at the firm level), our dataset includes system-specific drivers of vertical integration, allowing us to develop and exploit an instrumental variables strategy that overcomes many of the traditional problems in testing for complementarity in organizational design. Specifically, because our dataset includes (a) similar measures of the contracting environment for each system, and (b) we control for the system-specific drivers in our analysis, the identification in this paper results from measured differences in the contracting environment across systems within a given automobile model. By exploiting within-model variation in the contracting environment, we develop and implement an instrumental variables strategy that allows us to distinguish contracting complementarity from firm-level fixed effects in governance choice.

Though we are cautious in our interpretation, the empirical exploration uncovers a consistent pattern of support for the complementarity hypothesis. First, using instrumental variables to account for the endogeneity of the vertical integration choices for other systems within a model, the probability of vertical integration for each automobile system increases in

share of other systems that are vertically integrated. Second, even when including system-specific measures of the contracting environment, the contracting environment associated with other systems has a significant impact on governance. Third, the degree of correlation in contracting is empirically related to measures which are likely associated with the marginal returns to system-to-system integration activities. Finally, though our dataset is not large enough to undertake a structural analysis of individual system-to-system “pairs,” the degree of correlation seems to be highest for those “pairs” where the marginal returns to integration and coordination are likely most important. While our interpretation of these findings takes account of the small size of our dataset and the inherent challenges in assessing the economic drivers of organizational design, the results do suggest that assuming away contracting complementarity may be problematic in contexts where coordination activities are both important and difficult to monitor.

The remainder of the paper is organized as follows. The next section introduces the concept of contracting complementarity and contrasts it with the traditional *transactional* focus of prior theoretical and empirical research. We then undertake a qualitative assessment of product development contracting choices in the automobile industry, and the potential for contracting complementarity in this environment. Section IV develops a simple formal model of contracting complementarity, and Section V derives a formal empirical framework for testing this hypothesis. After a review of the data, Section VII reviews our key empirical findings. A final section concludes.

II. Transactions and the Unit of Analysis in the Economics of Contracting

Most theoretical research on the drivers of vertical integration assumes the “transaction” as the central unit of analysis for studying contracting choices. Building on the analysis of Williamson, researchers in both transaction cost economics and the property rights literature emphasize the role of a) asset specificity, b) uncertainty, c) opportunism and d) contracting costs in shaping the ability to provide efficient investment incentives through endogenous ownership structure. Theoretical treatments of contracting assume that difficulties in writing enforceable contracts that include detailed contingencies leave formal ownership over assets as a key mechanism determining individual investment incentives.

In part because of the theoretical literature’s focus on asset specificity and opportunities

for hold-up at the transaction level, empirical research on contracting has mostly focused on individual contracting opportunities (*see* Tirole (1999) and Whinston (2002) for a review of this literature). For example, in Monteverde and Teece's well-known study of the automobile industry, variation in asset specificity and the potential for hold-up for each component are linked to the component-level vertical integration choice (Monteverde and Teece, 1983).

Focusing at the "transaction" level is appropriate in those cases where the key issues of hold-up and opportunities for rent extraction occur at the same level of analysis. For example, in Joskow's study of coal plant and coal mine contracting, co-location of the coal plant and coal mine was shown to have a substantial impact on the key contracting choice – whether the coal plant was owned (or the length of contract with) the coal mine. At least in part, the persuasiveness of Joskow's evidence depends on the precise and nuanced match between the assumptions (and predictions) of the theory and his empirical setting.

The match between theory and evidence is often more difficult to justify, particular as one examines more complex contracting settings . For example, the relative availability of data about contracting practices in manufacturing firms has led to a sizeable literature focusing on the multiple contracting decisions of a single (or small number) of firms, taking each contracting choice as independent of each other (Monteverde and Teece, 1983; Masten, 1984; Masten, Meehan and Snyder, 1991). While these studies have identified the transaction-specific determinants of vertical integration, they abstract away from the possibility that an individual contracting choice might depend on the contracting choices made across the firm's contracting opportunities. By ignoring the potential for interactions among governance choices, transaction-specific approaches to governance may inaccurately capture how firms coordinate their governance choices.

In contrast, the potential for interactions among contracting choices within manufacturing firms has been long recognized by product development researchers. More precisely, the qualitative evidence from the product development literature emphasizes the potential for complementarity among the contracting choices a firm makes within its product development activities. For example, the product development literature emphasizes the centrality of system interfaces for assessing the costs of coordination (Alexander, 1964; Suh, 1990; Eppinger and Ulrich, 1994). In the absence of a well-designed interface between components, optimizing the

performance for each requires extensive (and difficult-to-monitor) coordination across component developers. The costs of such coordination are substantially lower if *all* component developers are within the same firm, with the potential for complementarity across contracting choices. In such a setting, though governance choices may be observed at the component level, the economic drivers of contracting must be analyzed at the system level, to account for potential contracting complementarity.

While the precise mechanism by which contracting complementarity arises is likely more subtle than the explanations offered by the product development literature, the potential for interactions among contracting choices is particularly high, given the theoretical requirements. As is well emphasized in the incomplete contracting literature (Grossman and Hart, 1985; Hart and Moore, 1990; GHM hereafter), the sensitivity of incentives to ownership choices can only matter for activities or investments which cannot be separately contracted upon. Indeed, the potential for contractibility is a major stumbling block to empirical work in this area. In sharp contrast, the types of investments, activities, and decisions that are associated with cross-unit component development are precisely those which are most difficult to specify, contract upon, verify, or enforce. For example, when component development is outsourced, it is impossible (outside of expensive litigation) to verify that an independent component manufacturer has simultaneously undertaken the investments necessary to ensure effective interfaces with components made by other manufacturers and also not revealed the trade secrets learned through that process to competitors; in contrast, co-location, internal promotion incentives and ongoing internal documentation may ensure such both effort provision towards integration and secrecy when both components are designed and manufactured within the firm. As a result, the incentives to invest in integration will be higher when the firm chooses to keep all of these activities under its control, yielding complementarity in contracting across the contracting choices under the firm's control.¹

Whether driven by traditional transaction cost concerns or phenomena more closely related to the property rights literature, contracting complementarity will have important implications for the organization of product development activities. Consider the interpretation

¹ While we emphasize complementarity across contracting choices, Azoulay (2002) has emphasized the potential for substitutability in contracting when there are important limitations on the resources available for product development within the firm.

for the increased (and clustered) use of outsourcing. While most researchers interpret the increased use of outsourcing of non-core activities as a firm-level “strategy,” contracting complementarity suggests that extensive use of outsourcing might arise from the interdependent returns to individual vertical integration choices. While most studies of complementarity have examined the relationship among distinct organizational practices (Ichniowski, Shaw and Prenusshi, 1997; Athey and Stern, 1999; Cockburn, Henderson and Stern, 2000), complementarity across distinct activities may be an additional useful approach towards studying the role of complementarity in organizational form.

III. Contracting Complementarity in Automobile Product Development

This section extends the conceptual argument of the last section in order to examine the potential for contracting complementarity in automobile product development. Drawing on a multi-year study of automobile product development by one of the authors, our argument is based on a detailed qualitative understanding of the drivers and impact of contracting and vertical integration in this setting.

Automobile product development contracting opportunities can be decomposed into four distinct levels of analysis: the entire car, key systems, sub-systems, and individual components. From a purely Williamsonian perspective (emphasizing the primacy of the most “micro” level of transaction), components are the most fine-grained unit of analysis that could be employed in studying contracting in automobile product development. However, beginning in the early 1980s, many companies undertook a more integrated approach to contracting in order to outsource “non-core” activities, to reduce overhead, and to gain access to superior supplier capabilities. As a result of this change in the contracting practices of the industry (which coincided with the rise of Japanese automakers who were known to rely heavily on structured outsourcing arrangements), the decision to outsource over the past twenty years is made at (at least) the sub-system level (*see* Fine and Whitney, 1996), and certainly key interactions determining the difficulties in product take place in (at least) the sub-system level.²

Furthermore, by the 1990s, new technology greatly increased the importance of

² This can be contrasted with the component-by-component contracting which had been the historical norm up until the early 1980s.

interaction or “integrality” across entire vehicle systems (e.g., across seats and instrument panels).³ In particular, increased electronic content across all systems of the car (from lumbar support in seats to ABS braking systems) was increasing the complexity and system-to-system dependence of each system within the automobile. As a result, the importance of coordination across system development greatly increased throughout the 1990s.

Thus, while most prior analysis of product development contracting focuses exclusively on component-level drivers, it may be useful to consider the impact of system-to-system interactions. For example, in perhaps the most noted product development failure of the last decade, the Ford/Firestone debacle had its roots in the failure of coordination across two systems, one of which (tire design and specification) was outsourced. To the best of our knowledge, prior research has not systematically examined the role of interdependencies in contract choice, nor has the rise of system-level contracting been formally assessed.⁴

While ensuring efficient investment in component technologies can often be achieved through formal contracting, providing incentives for overall vehicle performance and the integrality of parts is much more difficult to achieve. Consider the case of cellular telephones. In the luxury car market, a key (though recent) design challenge has been the integration of the cellular telephone sub-system into the audio system. In the integrated design, the cellular telephone would share a circuit board and control panel with the audio system, and these would, in turn, interface with the antennas, speakers, and microphone. In contrast, a simpler design would simply maintain the cell phone’s circuitry as separate from the audio system. Overall, the integrated design has several performance and cost advantages, such as better sound quality and less bulk, since the telephone could share speakers, circuitry, and features with the audio system. However, the more complex, integrated design would require extensive coordination between the auto manufacturer and the cellular telephone supplier during product development, as the specifications for the audio circuit board would interact with those for the telephone. The simpler design facilitates outsourcing production of the cellular telephone components, with little overlap between manufacturer and supplier during product development, but perhaps with sound

³ For further discussion of integrality in product development, see Ulrich (1995).

⁴ It is useful to emphasize the substantial financial stakes involved in these decisions. Automobile product development is perhaps the largest single area of development investment in the economy, and design excellence and vehicle performance are central to the establishment and sustainability of competitive advantage of firms in this global market.

and size performance penalties. At its heart, the development of an integrated cellphone/audio system requires investments in coordination and integrality that may only be able to be achieved by maintaining in-house cell phone and audio product development.

Several factors limit the ability of automobile manufacturers to provide the same incentives for (non-contractible investments in) coordination to suppliers as they are able to provide to internal product development teams. First, incentives for cross-system performance may be easier to achieve internally. Most car companies maintain a “vehicle integrity” organization with responsibility for ensuring that system-to-system interaction are being adequately considered, and members of these teams often have (formal) authority over internal engineers in particular systems development projects.⁵ While these managers have limited abilities to coordinate directly with suppliers, individual activities cannot depend on firm hierarchy when the coordination activities are across firm boundaries. As well, the marginal cost of ensuring a given level of coordination is often much lower in the context of internal development, as product development teams may be co-located, are more likely to speak the same language; as well, while internal teams can be focused exclusively on a single project (allowing time for investments in coordination activities), suppliers are often working on multiple projects, and it is difficult for the manufacturer to precisely observe the allocation of time (and constraints on time) for particular product development activities performed by a supplier.

Second, even if the costs of writing contracts with in-house and external teams is similar, trade secrecy concerns severely limit the ability to ensure effective coordination across systems when system development is outsourced. When product development occurs internally, different system groups (e.g., the seat system and body system groups) are able to freely exchange and share information, data, and design plans. In contrast, external suppliers may expose highly confidential trade secrets.⁶ As a result, the nature of communications and interactions that occur across firm boundaries are far more structured than would occur internally. When considering what information to share with suppliers, the benefits to coordination and integration on the

⁵ Clark and Fujimoto (1991) describe the role of the “heavyweight project manager” in the context of Japanese manufacturing.

⁶ For example, “early” spy photos of vehicles in development are highly sought after by trade publications such as *Automotive Weekly*, and suppliers have been sued for using their access to cause competitive harm through trade secrecy violations.

current design are traded off against the revelation of information about data and design plans within the firm.

Third, while supplier incentives are closely linked to the verifiable terms incorporated into the contract, internal teams may be able to be monitored and provided incentives on the basis of subjective performance data. For example, while the observed seat defect rate is a measure that a seat supplier may agree to have incorporated into a contract, a seat supplier will not accept compensation on the basis of qualitative customer satisfaction ratings (in part, because the manufacturer may be able to distort such data in order to avoid or lower payments). As well, internal incentives can both be in the form of direct compensation and bonuses, as well as in the form of promotion incentives, where subjective evaluation may be particularly important when higher levels of the hierarchy are associated with a smaller number of open positions.

The potential for contracting complementarity arises from trading off the benefits from improved coordination with the incentive costs relating to the ability to offer high-powered incentives to external supplier. In particular, the benefits of investing in coordination are substantially higher if *all* development work is being conducted within the same firm. For example, since trade secrecy concerns limit the flow of information when one system is outsourced, the returns to internal development of other systems is lower if this constraint limits the ability to ensure effective coordination. Since the marginal cost is higher, the equilibrium quality level associated with managing these interactions (and therefore the marginal returns to vertical integration) will be lower. As a result, though contracting choices may be observed at the system level, there may be complementarities in contracting across systems.

Taken together, our qualitative evidence suggests that, while individual transactions are conducted at the component (or sub-system) level, the increased importance of system-to-system interactions suggests that it is important to incorporate such effects in order to evaluate the key incentive and coordination problems that firms face in the product development process. Second, the structure of contracting and incentive provision in automobile product development raise the possibility of contracting complementarity across system vertical integration choices.

IV. A Simple Model of Contracting Complementarity

Building on these descriptive accounts of automobile product development, this section develops a simple model of contracting complementarity even when the *ex ante* cost of specifying contracts is the same whether or not the system is outsourced. In other words, rather than simply assuming that contracting complementarity arises coordination needs or technological interdependencies, we link complementarity to specific features of the contracting environment. Though simple, our model provides a concrete example of how contracting choices may become interdependent, providing a formal motivation for the empirical work we conduct in the remainder of the paper.

The Firm's Objective Function

We consider a simple production environment where the automobile producer (the “firm”) must contract for the development of two automobile systems, A and B, in order to produce a new automobile model. While system-specific performance is important, overall performance also depends on the level of system-to-system integration. Even if integration requires no additional effort or costs on the parts of the development teams, we assume that effective integration imposes additional costs on the firm, and that some of these costs depend on the chosen vertical structure. Specifically, we assume that effective integration requires the disclosure of crucial model-level design details to product development team member, and that maintaining these details as a secret is crucial for profitable entry into the marketplace.⁷ In other words, total profits depend on the performance of each system, whether the systems are integrated and whether the plans remain a secret:

$$\Pi = f^A(y_A; Z_A) + f^B(y_B; Z_B) + f^I(x_I; Z_I) - c(\theta(y_A, y_B, x_I))$$

For each system, performance depends on the pre-existing capability level of the team chosen, the effort level devoted by that team to that system, and a random component. For system i , let $y_i = 0$ be defined as an outsourced team and $y_i = 1$ as in-house development. Then, when choosing between in-house and outsourced development, system-specific performance will be equal to:

⁷ Perhaps give an example here drawn from our more specific discussion in Section III.

$$f_i^{y_i} = h(Z_i^{y_i}) + e_i^{y_i} + \eta_i \quad (y_i \in \{0,1\})$$

There will be variation across model-systems as to whether external or in-house teams have a greater pre-existing capability level (or current capacity to complete the work). Indeed, this form of variation— factors impacting system-level performance but unrelated to the interdependencies among systems – is the key to our empirical identification strategy we describe in the next section.

Beyond some baseline level, integration requires disclosure ($x_I = 1$), the benefits of which are independent of the chosen ownership structure. However, the probability that model-level design information is disclosed to competitors, θ , increases from θ_L to θ_H when $x_I = 1$ and either $y_A = 1$ or $y_B = 1$. In other words, in the case where the integration benefit is realized, the disclosure probability depends on whether at least one of the systems is outsourced.⁸ Taken together, these assumptions allow us to consider the firm’s overall objective function:

$$\text{Max}_{y_A, y_B, x_I} \Pi = \sum_{i=A,B} (h(Z_i^{y_i}) + e_i^{y_i}) + f^I(x_I) - (x_I(1 - y_A y_B)(c(\theta_H) - c(\theta_L)))$$

The Contracting Environment

Optimal contracting choices are based on the relative benefits of in-house versus supplier development and how these choices interact with the potential costs of disclosure. While the *ex ante* costs of writing contract specifications is the same for both in-house and external teams, *ex post* differences in the contracting environment lead to systematic differences in the effort provision of in-house versus external teams. Specifically, performance is observed with a lag, and the terms of contracting are subject to renegotiation when performance is observed.⁹

Consider the expected difference in bargaining position for in-house versus external product development teams once performance is observed. External suppliers will have relatively little bargaining power, as they will likely have no ongoing contractual relationship with the firm. As such, when contract specifications are not met (e.g., a system-specific failure occurs), the auto manufacturer can (and will) enforce whatever contractual penalties are

⁸ The baseline probability of disclosure is greater than zero in order to be consistent with the idea that disclosure itself is non-contractible, as the “source” of competitive intelligence cannot be verified. As well, while the current model assumes that the potential for expropriation does not increase when *both* teams are outsourced (relative to θ_H), we could easily accommodate this extension as long as $c(\theta(1,1,1)) - c(\theta_H) \leq c(\theta_H) - c(\theta_L)$.

⁹ More precisely, it may be the case that the timing associated with observing a *system-specific failure* is uncertain, as it depends on the accumulation of user evidence (e.g., consumer complaints, crash rates, etc.). The key assumption is that the expected ability to renegotiate contracts differs across in-house versus external suppliers at the time of initial contracting.

specified. As a result, auto manufacturers and their suppliers can (and do) litigate disputes through arbitration or formal litigation on a regular basis (Ref). By writing an enforceable contract with severe penalties in the case of system failure, the firm can induce a high level of effort supply by choosing an external supplier.

In contrast, enforcing severe penalties against the members of an in-house product development team is more difficult. By the time that performance is revealed, team members will be working on *new projects* for the firm; as a result, the threat of hold-up counter-balances the threat of penalties by the firm. In other words, the continuing involvement of the in-house teams with the firm reduces the ability of the firm to commit to enforceable penalties associated with system failure.¹⁰ Moreover, the ability to specify performance incentives for individual employees is limited by the fact that (a) employees are dispersed throughout the firm and so the cost of enforcing provisions may have a large impact on projects throughout the firm and (b) individual liquidity constraints constrain the ability of the firm to specify monetary damages of the type that are routinely used in supplier contracts. Even though the ex ante costs of specifying contracts is identical, differences in the ex post environment mean that the equilibrium level of effort for in-house development will be lower than the effort level associated with external contracting (i.e., $e^1 < e^0$).¹¹

Finally, we also assume that the firm cannot specify specific penalties for trade secrecy violations; while an occasional instance of industrial espionage will result in a supplier being caught “red-handed,” most expropriation occurs without the firm’s knowledge and with few clues as to the precise source of the disclosure of intelligence to competitors.

¹⁰ Of course, as a repeated relationship, it is likely that internal effort incentives may be impacted by relational contracts, which may ameliorate some of the most severe incentive problems (Baker, Gibbons, and Murphy, 2002). Indeed, for non-contractible dimensions of effort, relational contracting may be superior to formal contracts. However, the key point is that *ex post* differences in the ability to renegotiate will result in *ex ante* differences in contractual specification.

¹¹ As discussed earlier, it is possible that $e^1 > e^0$ as a result of relational contracting. While this does not impact the comparative statics examined in this paper, it may hold implications for interpreting the drivers of internal versus external product development. In particular, if internal development yields similar effort provision to external contracting, then the system-specific capability advantage offered by external suppliers must be greater than the efficiency losses due to expropriation in order to offer the contract to an external supplier.

Optimal Contracting, Disclosure and Complementarity

The firm simultaneously chooses whether to vertically integrate each product development team and whether to facilitate integration through disclosure. The only source of interdependency across vertical integration choices is through the disclosure decision, whereby the costs of disclosure are raised as a result of external contracting for either system. This structure yields the main insight from this simple model:

Proposition 1: $\Pi(y_A, y_B, x_I)$ is supermodular in y_A , y_B , and x_I .

Proof:

Supermodularity can be shown in this model as the result of complementarity between each of the following three pairs $((y_A, x_I), (y_B, x_I), (y_A, y_B))$. Let us consider complementarity between y_A and x_I first (i.e., we need to show that $\Pi(1, y_B, 1) + \Pi(0, y_B, 0) \geq \Pi(1, y_B, 0) + \Pi(0, y_B, 1)$ for $y_B = 0$ or 1). When $y_B = 0$, both sides of the condition are equal, since the firm bears $c(\theta_H) - c(\theta_L)$ for both cases where $x_I = 1$ (the first and last terms). However, when $y_B = 1$, the inequality is strict, since the firm only bears $c(\theta_H) - c(\theta_L)$ under $\Pi(0, 1, 1)$, and all the remaining terms cancel out. A similar argument holds for complementarity between y_B and x_I . Finally, setting $x_I = 0$, $\Pi(1, 1, 0) + \Pi(0, 0, 0) = \Pi(1, 0, 0) + \Pi(0, 1, 0)$, since there is no interdependency in the absence of disclosure. However, $\Pi(1, 1, 1) + \Pi(0, 0, 1) > \Pi(1, 0, 1) + \Pi(0, 1, 1)$ since the firm only bears $c(\theta_H) - c(\theta_L)$ once on the left-hand side and for both conditions on the right-hand side of the inequality.

In the absence of disclosure by the firm, this simple model has no interdependencies between the system-level choices. However, by introducing a non-contractible element which is “shared” across each system choice (i.e., the non-contractibility of the trade secrecy clause and the fact that the probability of expropriation increases most steeply with the first instance of external contracting), we can derive contracting complementarity within this simple model where ex ante contracting costs are similar for both internal and external teams. Simplifying our earlier notation so that Z_i is equal to system-specific factors favoring vertical integration for system i , Proposition 1 allows us to derive the key comparative statics motivating our empirical strategy:

Remark: y_A^* , y_B^* , and x_I^* are weakly increasing in Z_A , Z_B , and weakly decreasing in $c(\theta_H) - c(\theta_L)$.

Proof:

Since Z_i has a monotone relationship with each of the y_i , the comparative statics with respect to Z_i are a direct consequence of Milgrom and Shannon (1995, Proposition 4).

In other words, an increase in pre-existing in-house capabilities for one system not only increases the marginal returns for in-house contracting for that system, but also increases the marginal returns to in-house contracting for other systems for that automobile model. It is this intuition that we use to identify complementarity in our empirical work which we pursue in the remainder of the paper.

IV. An Empirical Framework

This section uses the theoretical structure in the prior section to develop an empirical strategy to test for the presence of complementarity among organizational design decisions. We build on a recent applied econometric literature (Arora, 1995; Athey and Stern, 2000) that offers a precise approach for distinguishing complementarity from fixed “firm-level” factors that may (spuriously) induce correlation across the contracting choices within the firm. We begin by developing an empirical framework in the context of the model from the previous section, and then extend that framework so that we can adapt it to our specific empirical setting. As well, we discuss several potential relaxations of the framework that allow us to test the key assumptions we are making to test for complementarity in this specific empirical application.

Suppose that for both Y_A and Y_B , the separable benefits (and costs) to vertical integration observable to the firm is a vector, Z_i . Z_i is composed of two distinct parts. Both the firm and econometrician observe z_i , while χ_i is a choice-specific mean-zero shock observed by the firm but unobservable to the econometrician. Moreover, the elements of χ may be correlated; we assume there is a firm-level mean-zero “fixed effect” (ξ_i) which impacts the overall propensity of the firm to vertically integrate (i.e., $\chi_{i,t} = \xi_i + \varepsilon_{i,t}$). As well, in line with Proposition 1, the returns to each choice are interdependent: the marginal returns to vertical integration for Y_A increase when the firm vertically integrates into Y_B . We assume this interdependence takes the

form of a fixed component across all firms, which we define as λ .¹² The firm optimizes across its choices of Y_1 and Y_2 , yielding the following maximization problem:

$$f_t = \lambda(Y_{A,t} * Y_{B,t}) + (\beta_{Y_A} + \beta_{Y_A Z_A} Z_{A,t} + \chi_{A,t}) Y_{A,t} + (\beta_{Y_B} + \beta_{Y_B Z_B} Z_{B,t} + \chi_{B,t}) Y_{B,t}$$

To understand the relationship between this performance equation and optimal choice behavior (as well as the key issues associated with empirical measurement), it is useful to consider the demand condition for each practice:

$$Y_{i,t} = 1 \text{ if } \lambda Y_{-i,t} + \xi_t + (\beta_i + \beta_{iZ_i} Z_{i,t} + \varepsilon_{i,t}) > 0, Y_i = 0 \text{ else}$$

In this context, $\lambda > 0$ can be interpreted as the degree of complementarity between Y_A and Y_B , and ξ is an unobserved firm-level effect which (perhaps spuriously) induces correlation among the firm's decision regarding Y_A and Y_B .¹³ The goal of empirical work in this context is to estimate the underlying parameters of the “organizational design production function,” focusing in particular on λ , the degree of contracting complementarity. It is relatively straightforward to see that the conditional correlation between Y_A and Y_B will result in a biased estimate of λ . Consider a linear probability model:

$$Y_{it} = \beta_i + \lambda Y_{-i,t} + \beta_{Z_i} Z_{i,t} + \eta_{i,t}$$

where the error component can be rewritten:

$$\eta_{i,t} = \xi_t + \varepsilon_{i,t}$$

However, since $E(Y_{-i} * \eta) > 0$ (since the probability that $Y_{-i} = 1$ is increasing in the level of ξ), $\hat{\lambda}_{OLS}$ is biased.

An instrumental variables estimator, however, does provide consistent estimates of λ . As well, this framework yields a natural (and rich) set of instruments based on the observability of choice-specific exogenous drivers. Note that the argument for consistency under instrumental variables depends on $E(Z_{-i} \chi_i) = E(Z_{-i} \xi) = 0$. As a result, the elements of Z_{-i} – factors which drive the adoption of Y_{-i} but are uncorrelated with χ_i – provides a natural set of instruments for Y_{-i} in the context of the equation for Y_i . As emphasized by Arora (1995) and Athey and Stern

¹² In line with the model in Section IV, λ is a function of $c(\theta_H) - c(\theta_L)$ and Z_I . We are simply observing that degree of complementarity that results from this more structural relationship.

¹³ As well, ξ may reflect fads or managerial preferences not actually linked to long-term performance.

(1999), the lack of choice-specific instruments (the Z_i 's) has limited the feasibility of empirical work on complementarity in many contexts.

In contrast, our original dataset of automobile product development projects includes several exogenous factors specific to each system that provide instruments for the vertical integration drivers for that system. In particular, we observe factors for each system within the automobile, and so, for each system Y_i , we include Z_i directly and then use Z_{-i} as instruments for Y_{-i} within that model for that system. For example, we observe specific factors such as the degree of prior sunk internal investments or the presence of system-specific worker skills shortages for each system in the automobile. By including these variables directly into the equation and relying on instruments from other systems to identify the complementarity parameter, our identification is the consequence of *system-specific differences in the contracting environment which also result in differences in contracting choices*.¹⁴

While this discussion of a two-system choice highlights the main econometric issues, applying this framework requires that we consider the interactions among seven distinct systems within each automobile in our dataset. We address the potential for multiple interactions in two distinct ways. First, we adapt our framework to estimate the “average” level of system-to-system contracting complementarity. To do so, we first calculate, for each system, the “average” level of vertical integration for *other* systems on that automobile model. Of course, aggregating across choices does not mitigate the endogeneity issues described above; however, we adapt the solution described above and calculate the “average” Z_{-i} for each observation, yielding instruments for Y_{-i} in our empirical analysis. Second, we supplement this “average” analysis with a nuanced assessment of system “pairs” (e.g., the specific interaction between brake and seat systems). Exploiting our detailed qualitative evidence and engineering knowledge regarding the specific system pairs which should be most subject to contracting complementarity, we are able to test whether the “average” level of contracting complementarity is driven by specific system-to-system product development challenges where non-contractibility (and non-observability) of effort is likely most problematic.

We also consider the possibility that the degree of complementarity may depend on the product development environment itself. For example, the returns to ensuring efficient

¹⁴ This strategy was suggested to us by the use of an analogous strategy to instrument for price in the context of differentiated products models in the industrial organization literature (Berry, Levinsohn, and Pakes, 1995; Bresnahan, Stern, and Trajtenberg, 1997; Hausman, 1997).

investment in coordinating across automobile systems may be higher when a model is conforming to “platform” requirements (and so must also be coordinated across multiple automobile models). We test for this idea by interacting system-specific drivers of vertical integration (such as a measure of platform requirements) with the “average” vertical integration choice on other systems. Extending our earlier argument regarding instrumental variables, we construct instruments by considering combinations of Z_i and Z_{-i} (e.g., $(Z_i * Z_{-i})'$). In so doing, we are extending the empirical framework in order to test for the nuanced implication that contracting complementarities may be more important in particular contracting and product development environments.

VI. The Data

Sample and Methods

This study uses a proprietary, self-collected dataset based on a multi-year study of contracting and product architecture in the global auto industry. We studied luxury performance cars (defined by *Consumer Reports* as vehicles priced above \$30,000 in 1995) and the companies included in the sample are drawn from Europe, the U.S. and Japan, and account for roughly 90% of revenues in the global luxury performance market. As flagship vehicles developed in different environments over time, wide variation in contracting practices (and the contracting environment) was expected. By focusing on a single vehicle segment, we limit the measurement problems that arise from combining combines information from different vehicle types.¹⁵

The unit of analysis is the automotive system, and includes comprehensive information about seven systems for twenty automobile model-years developed between 1980 and 1995.¹⁶ The data were collected through on-site interviews at all companies in the study. Over 1000 people were interviewed, including CEOs, chief engineers, project managers and system engineers involved in development of each vehicle for each time period in the study. All

¹⁵ We collected data focused on the same components in a single vehicle segment in the auto industry in order to remove possible measurement problems caused by a data set which combines information from different vehicle types, such as that of Clark and Fujimoto (1991), or from different component types, such as Masten, Meehan and Snyder (1989).

¹⁶ More precisely, the overall dataset includes information about 8 distinct car models, many of which are observed at (roughly) five-year intervals, resulting in 20 total “model-years” from which to draw system data. One of these model-years is dropped in the analysis due to incomplete data across all systems of the automobile, resulting in 133 observations across 19 models.

participants were assured that only aggregate data would be presented, and confidentiality agreements were signed with each company.

Data collection proceeded in several stages. After signing an agreement with each firm, a letter was sent requesting interviews with relevant project managers, system engineers, design engineers, purchasing managers and manufacturing engineers for each vehicle for each time period. The relevant parties were identified by the corporate liaison for each company, and on-site meetings were arranged. To ensure data accuracy, interviewees were given an overview of the research project and definitions for key terms. Subjects were given a list of questions pertaining to the design and sourcing of components within their respective systems. The questions focused on principally objective information (e.g. number of parts in the body side) so as to minimize the likelihood of response bias. The interviews were conducted on-site at each company, in time intervals ranging from three days to three months. All interviewees were given the option of being interviewed in their native languages. US and European interviews were conducted in English and Japanese interviews were conducted in Japanese.¹⁷

After dropping one model-year due to incomplete data, the sample is composed of 133 car systems, drawn from nineteen distinct car model-years and across seven distinct systems: engine, transmission, body, electrical, suspension, steering, and brakes. Table 1 provides variable names, definitions, and summary statistics for the variables employed in the analysis (Appendix A provides the pairwise correlations for the whole dataset).¹⁸

Contracting Variables

The dependent variable throughout the analysis is VERTICAL INTEGRATION, the percentage of the system produced in-house, with 1 indicating in-house production of all components within that system.¹⁹ For each component, system, vehicle model, and time period, we have collected data on the make / buy decision outcome. The system measure is constructed by equally weighting the measure of each component within the system. Parts supplied to firms by wholly-owned subsidiaries, such as the Delphi division of General Motors, are treated as in-

¹⁷ All interviews were conducted by one of the authors. Professor Kentaro Nobeoka, a scholar with extensive experience in the Japanese auto industry, provided Japanese interview interpretation.

¹⁸ For reasons of confidentiality, company-specific data are not presented.

¹⁹ Masten et al (1989) use a similar measure at the component level. We believe system-level analysis captures a more complete measure of sourcing behavior. Moreover, since we can only measure systematic variation in the contracting environment at the system level, we conduct the analysis at this level of aggregation.

house. Parts produced by partially owned suppliers, such as Nippondenso (Toyota group), were treated as outside suppliers. Sourcing spanned the entire range from 0 (outsourced) to 1 (in-house production), with a mean of .48 and a standard deviation of .32. We also calculate VERTICAL INTEGRATION_i, which is the average value of VERTICAL INTEGRATION across all *other* systems within that model (by construction, the mean is identical to VERTICAL INTEGRATION). Consistent with the empirical framework described in Section V, VERTICAL INTEGRATION_i will be treated through the bulk of the analysis as an endogenous regressor; we calculate the instruments for VERTICAL INTEGRATION_i from within-model variation in the system-specific contracting environment.

System-Specific Contracting Environment Measures

The key measures for our identification strategy are four *system-specific* measures of the contracting environment. Since each of these variables is measured at the system level, there is (potentially) variation across systems within a given model-year. This allows us to calculate instruments, within each model year, for VERTICAL INTEGRATION_i that are not collinear with VERTICAL INTEGRATION in that model-year. The dataset includes two different types of system-specific measures: factors relating to pre-existing in-house capabilities/resources (SUNK COSTS and LOW CAPACITY), and factors relating to the intensity of the design and manufacturing challenge associated with that system (COMPLEXITY and PLATFORM). It is important to recognize that, from the perspective of the contracting choice for each system, there is a strong argument that each of these measures, described in some detail below, is econometrically exogenous. Investments in sunk assets and production capacity are made many years (perhaps decades) in advance of individual model-year contracting choices, and design and technology choices are made well in advance of the vertical integration choices for individual systems, based on factors unrelated to vertical integration.²⁰ However, recognizing that the argument for exogeneity for the factors relating to design/technology choices is less strong than for those variables relating to pre-existing capabilities, we first focus our analysis on the first of variables, before incorporating the full set of system-specific measures into the analysis.

We now turn to a more specific discussion of each of the system-specific measures.

²⁰ Novak and Eppinger (2001) consider the exogeneity of COMPLEXITY directly, finding that the exogeneity of COMPLEXITY cannot be rejected by a Hausman test.

LOW CAPACITY is a dummy variable indicating that, prior to contracting, the level of in-house capacity is insufficient to manufacture the system in-house (mean = 0.17). 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 VERTICAL INTEGRATION and LOW CAPACITY.

SUNK COST is a dummy variable indicating whether there is pre-existing in-house sunk investments for each system (mean = 0.13). Specifically, managers were asked whether or not existing plant equipment directly affected their design choices for the system, as systems are often designed around plant-specific process equipment investments. Overall, the existence of pre-existing in-house capital investment will tend to favor a positive relationship between VERTICAL INTEGRATION and SUNK COST at the system level. However, it is also possible that pre-existing manufacturing problems will reduce the perceived value of the investments measured by the SUNK COST dummy, limiting its impact on VERTICAL INTEGRATION.

Turning to factors related to system-specific design and technology choice, PLATFORM is a dummy variable equal to one for models with platform requirements where the component was designed to be used by more than one vehicle. Platform requirements could support in-house production through economies of scale achieved through parts sharing. For this reason, we hypothesize a positive relationship between PLATFORM and VERTICAL INTEGRATION.²¹ As well, 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), a process which may make the need to ensure efficient investment in coordination and integration even more important. For example, the Ford Taurus underbody greatly restricted design complexity on the Lincoln Continental underbody design that was built on the same platform. As a result, we expect that PLATFORM may interact positively with VERTICAL INTEGRATION._i.

As well, the degree of system-specific complexity should be positively related to VERTICAL INTEGRATION. As developed in Novak and Eppinger (2001), the degree of system-level complexity will impact the need for coordination across component elements of the system, encouraging in-house contracting. Our measure of system complexity draws on several

²¹ Consistent with transaction cost theory, we assume that although suppliers may be able to enjoy the same economies of scale, they will not pass along the full savings of platform sourcing.

measures, based on detailed system design and manufacturing data. For each system, we estimate product complexity on a scale from 0 to 1 (no complex system interactions to high product complexity) based on an unweighted average of characteristics of design complexity.²² For some systems, measures include characteristics such as “newness” - the degree to which a design configuration has been used in the company and in the vehicle. For example, product complexity in the suspension system is calculated as an unweighted average of three (0-1) measures: newness of the design, number of moving parts in the suspension and whether the suspension is active or passive.²³ The measure used in our analysis, COMPLEXITY (mean = .41), is the result of applying this procedure for each component within each system.

Model-Level Contracting Environment Measures

In addition to system-specific drivers of vertical integration, we observe two potential drivers of contracting at the model-year level (VOLUME and UNION). While these will not facilitate the identification of contracting complementarity across systems, these variables serve as controls to account for correlation in contracting choices at the model-year level. As well, the analysis will include specifications incorporating company fixed effects; because there is not sufficient variation across models, we exclude these model-year factors when we include company fixed effects in our empirical work.

Our first model-year measure, VOLUME, is the variable for vehicle volume. The volume measure is the overall company volume of automobiles produced in the model year.²⁴ While economies of scale in production favor in-house production if these scale economies cannot be realized with external contractors, it is possible that scale may interact in subtle ways with the ability to write and enforce contracts with external suppliers. For example, while BMW is much smaller than Toyota in absolute volume, Toyota’s luxury performance volume is much smaller than BMW’s. As a result, BMW may be able to command a larger, not smaller, ordering capacity with suppliers due to its much larger luxury performance market. Alternatively, 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

²² For each system, measures of complexity were chosen on the basis of system engineering principles. The complexity measures used are discussed in detail in Novak and Eppinger (2001).

²³ See Novak and Eppinger (2001).

²⁴ We have also experimented with a measure based on the *share* of volume devoted to luxury car production; this measure has no qualitative or statistical impact on our results concerning contracting complementarity (CHECK).

between VOLUME and VERTICAL INTEGRATION.

AS well, UNION is a dummy variable which is equal to 1 if *any* component is produced in house and 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 VERTICAL INTEGRATION.

*Technology and Location Controls*²⁵

Our dataset also includes four technology and location measures which are not predicted to have a direct impact on VERTICAL INTEGRATION but may impact the degree of contracting complementarity. While each of these measures was originally collected as instrumental variables for COMPLEXITY (discussed in Novak and Eppinger (2001)), they may also serve to mediate the relative importance of coordinating contracting choices across systems.

Three of these measures are observed at the system level. First, PERFORMANCE is a dummy variable equal to 1 if an individual system is associated with “high” system-specific performance goals. The importance of performance goals were provided by vehicle product managers, on a 0-10 scale, with 0 indicating no importance for product performance goals and 10 indicating that the vehicle competes based on high performance. Certain performance goals necessitate more complex product designs, such as more integrated architectures (Ulrich, 1995). For example, a result of designing to meet high top-speed capability is a body system consisting of tightly interconnected parts.²⁶ Since systems for which performance goals are very high are likely to be associated with high system-specific complexity, integration with *other* systems may be less important, and so PERFORMANCE may reduce the importance of contracting complementarity in contracting choice.

Similarly, SKILL SHORTAGE (mean = .15) is a dummy variable equal to 1 if key system-specific worker skills are absent within current plant locations. For example, it is much more costly to produce a body design featuring many complex manual welds in an area where workers are not trained in advanced welding. Vehicle product managers were asked whether the absence of worker skills played a role in design considerations for each system. Because SKILL

²⁵ *This sub-section is preliminary and is subject to revision .*

²⁶ This is due to the requirements for overall mass reduction in order to attain high top speeds.

SHORTAGE may constrain the system-specific contracting choices for individual components and systems, SKILL SHORTAGE may reduce the degree to which an auto manufacturer can coordinate contracting choices over systems.

Finally, TECHNOLOGY, the dummy for the state of technology, takes on a value of 1 for the year in which certain innovations, such as antilock brakes and new electronics technology in suspension systems, are introduced. This variable reflects technological innovations that have enabled increased product performance deliverable via modular components. To the extent that these improvements are system-specific, TECHNOLOGY may reduce the sensitivity to other contracting choices; alternatively, TECHNOLOGY may relax constraints within each system and so enhance the degree to which the firm is able to take advantage of the benefits of coordinated contracting choices. As such, while TECHNOLOGY may mediate the degree of contracting complementarity, we have no prediction as to its expected sign.

Finally, MAJOR 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 and Fujimoto, 1989). The firm has an opportunity to change product complexity in major changes, and we expect that in performance vehicles these changes should involve greater performance, and therefore greater product complexity. Since MAJOR is only observed at the model-year level, we include in specific specifications as an additional control for company-specific factors impacting the contracting choices of the firm.

System, Year, and Company Fixed Effects

We also calculate fixed effects for each of the seven automobile systems (SEATS are the excluded category), two time category dummies (1986-1990 and 1991-1996, with pre-1986 models falling into the excluded category), and eight company dummies (company dummies are suppressed to preserve confidentiality). The empirical analysis includes and excludes each of these control structures in order to identify the precise source of variation in the dataset driving our key findings and to highlight the robustness of key results to focusing on alternative sources of variation.

VII. Empirical Results

We now turn to the key empirical findings. The analysis is divided into several steps.

First, we present our core findings examining the sensitivity of the degree of vertical integration in any one system to the “average” vertical integration choice of other systems in that model. In this analysis, we highlight results that exploit our instrumental variables strategy that allows us to distinguish contracting complementarity from a firm-level “taste” for vertical integration, and the robustness of the results to various controls. We complement our instrumental variables analysis with a reduced-form approach which examines the impact of the instrumental variables themselves on contracting choice (in the spirit of Arora, 1995). We then examine how the degree of contracting complementarity might depend on factors in the contracting environment. We extend our instrumental variables strategy to estimate the impact of interactions between $VERTICAL\ INTEGRATION_{i,j}$ and specific factors impacting system-level contracting. Finally, we undertake a more nuanced analysis of specific system-to-system “pairs.” Based on our qualitative understanding of the product development process, we identify key pairs where contracting complementarity may be particularly important. Though the modest size of the dataset makes us cautious in our interpretation of our findings, our results accord with a simple model where the inability to contract with external suppliers for effective integration induces contracting complementarity among system-level vertical integration choices. Moreover, these complementarities are estimated to have a quantitatively significant impact on the industrial organization of product development in the global automobile industry.

An Instrumental Variables Approach to Testing for Contracting Complementarity

We begin in Table 2 with a number of simple OLS regressions of $VERTICAL\ INTEGRATION$ on $VERTICAL\ INTEGRATION_{i,j}$. We first present the relationship with no controls, and then introduce a complete set of system effects (SEATS is the excluded category). While most of the system effects are significant (and different than each other), the most striking result is the large and significant coefficient on $VERTICAL\ INTEGRATION_{i,j}$. The final two columns of Table 2 include a progressively more complete set of transaction-specific drivers of vertical integration drivers; (2-4) includes all of the measures from the dataset, as well as a full set of system and year controls. While the estimated size of the effect is reduced by about 20% relative to (2-1), the correlation between $VERTICAL\ INTEGRATION$ and $VERTICAL\ INTEGRATION_{i,j}$ remains extremely large, particularly compared to the size of the effects associated with the system-specific drivers of vertical integration. Each of the estimated

elasticities for the system-specific drivers is smaller than the estimated elasticity of VERTICAL INTEGRATION and VERTICAL INTEGRATION_{*i*} (.70).

Of course, the conditional correlation captured in Table 2 may be spurious, driven by firm (or model)-specific unobservables inducing a high correlation among the contracting choices of the firm across system. As we have discussed earlier, we address this strategy exploiting an instrumental variables strategy in which, for each of the regressions in Table 3, the instruments for VERTICAL INTEGRATION_{*i*} are the mean levels of the other variables included in the specification for other systems but for model *i*. Since some measures, such as UNION or L(VOLUME) do not vary across systems within each car model, the excluded instruments depend only on the system-specific drivers of vertical integration. For the specification in (3-1), for example, the excluded instruments is the average (for other systems for that car model) of LOW CAPACITY and SUNK COST. When system fixed effects, year controls, and model-year drivers are included, both LOW CAPACITY and SUNK COST are individually significant (at the 10% level); more importantly, the instrumental variables coefficient on VERTICAL INTEGRATION_{*i*} is positive and significant (and larger in magnitude than the OLS coefficient). In terms of quantitative importance, a shift in the contracting environment that induces a one standard deviation shift in VERTICAL INTEGRATION_{*i*} (0.25) is predicted to have a .28 shift in the predicted value for VERTICAL INTEGRATION for an individual system.

The final two columns of Table 3 include PLATFORM and COMPLEXITY. Consistent with our earlier approach, we continue to instrument for VERTICAL INTEGRATION_{*i*} with the average level of the system-specific measures for other systems in that model. While we are cautious about interpreting these results since there may be model-specific factors impacting both technology choices such as COMPLEXITY and contracting, it is useful to compare how the inclusion of these factors impact the estimated degree of contracting complementarity. While neither of the two new measures is individually significant when other controls are included, the coefficients on VERTICAL INTEGRATION_{*i*}, SUNK COST, and COMPLEXITY remain similar (at similar levels of statistical and quantitative significance). Indeed, even when company fixed effects are included in (3-4), the coefficient and precision of VERTICAL

INTEGRATION_i remains similar and larger than the impact estimated using OLS.²⁷

Taken together, the results in Table 3 provide quite interesting evidence in favor of interdependency in the level of vertical integration across systems within automobile product development. Relative to factors incorporated from a transaction-specific approach to vertical integration, VERTICAL INTEGRATION_i has the single most decisive influence on explaining within-system variation in the degree of vertical integration. Moreover, rather than reflecting unobserved firm-level factors, the interdependency between vertical integration choices is shown to be identified even if one only depends on the portion of VERTICAL INTEGRATION_i that is predicted to vary according to observable system-specific drivers.

A Reduced-Form Approach to Testing for Contracting Complementarity

Table 4 explores how contracting for a given system is impacted by the contracting environment for *other* systems by directly including the excluded instruments from Table 3 in an OLS specification. This reduced-form strategy follows Arora (1995), who derives the conditions under which a reduced-form approach to testing for complementarity in organizational design is possible. Unfortunately, in most applications, the ability to provide persuasive evidence of complementarity through instrumental variables (or the reduced-form approach) is limited by the inability to provide persuasive evidence for the exogeneity of specific instruments. However, in the current application, the identification argument is more subtle. Specifically, because our dataset includes (a) similar measures of the contracting environment for each system, and (b) we control for the system-specific drivers in our analysis, the identification in this paper results from *measured differences in the contracting environment across systems within a given automobile model*. The reduced-form approach highlights this feature; if the correlation was driven by similarities in the environment across systems, then the instrumental variables would be collinear with the system-specific direct effects included in each model.

In (4-1), both LOW CAPACITY and SUNK COSTS are included, as well as LOW CAPACITY_i and SUNK COSTS_i. Both the direct effects of LOW CAPACITY and LOW CAPACITY_i are statistically and quantitatively significant (interestingly, a one-standard

²⁷ In unreported specifications, these instrumental variables estimates are robust to: (a) including all of the measures from the dataset (PERFORMANCE, TECHNOLOGY, SKILL SHORTAGE, etc...). (b) the functional form for variables such as VOLUME, and (c) turning VERTICAL INTEGRATION into a dummy variable equal to one for various “cut-offs” for the degree of vertical integration.

deviation of either variable is predicted to have a similar impact). The remaining specifications, which include PLATFORM (and PLATFORM_i) and COMPLEXITY (and COMPLEXITY_i) display a similar pattern. Specifically, even after controlling for system fixed effects and year controls, both the direct effects and instrumental variables are individually significant.²⁸ Together with the instrumental variables results from Table 3, these results suggest that the strong pattern of correlation in contracting across systems within a model is not simply a firm-specific effect but is related to *variation* in the contracting environment within a given company and model-year.

Does the Contracting or Technology Environment Impact Contracting Complementarity?

Moving beyond our core finding of an empirical relationship across contracting choices, the sources of contracting complementarity can be assessed by examining how the degree of correlation in contracting varies with other features of the contracting and technology environment. In particular, Table 4 considers the impact of interactions between VERTICAL INTEGRATION_i and specific system-specific technology variables and drivers of vertical integration. Because of the limited size of our dataset, we explored these interactions by combining our qualitative understanding of automobile product development with the theoretical model developed in Section IV. Among the system-specific drivers of vertical integration, two potential relationships seemed most promising. First, and perhaps most importantly, the returns to effective coordination and integration are particularly high for PLATFORM systems, as the costs of system failure may require costly adjustments across multiple automobile models. In contrast, the ability to exploit across-system integration may be reduced for highly complex systems, reducing the returns to coordinated contracting choices. As well, technology and location factors (PLATFORM, SKILL SHORTAGE, and TECHNOLOGY) might also impact the returns to coordinated contracting. For example, when a particular system is the focus of performance improvement or is highly constrained in the resources available for effective development or manufacturing, the degree of observed contracting complementarity may be lower.

²⁸ It is useful to note that, while the basic pattern of correlation remains, the results on individual coefficients becomes noisier when all of the variables in our dataset are included simultaneously. The instrumental variables approach presented in Table 3, of course, take account of this collinearity when calculating the precision of the instrumental variables estimates.

Each of these relationships is explored in Table 5. For each specification, we extend the instrumental variables strategy from Table 3, constructing instruments by multiplying each system-specific vertical integration driver and the instrumental variables for VERTICAL INTEGRATION_i employed in Table 3.²⁹ The results are quite suggestive. First, and perhaps most importantly, the direct effect of VERTICAL INTEGRATION_i continues to quantitatively and statistically significant across specifications. As well, VI_i*PLATFORM is positive and significant in the first two specifications; however, this estimate becomes insignificant after the inclusion of the full set of controls in the final specifications. As well, both VI_i*PERFORMANCE and VI_i*SKILL SHORTAGE are consistently negative and significance across all specifications we attempted. Though we are limited in our exploration of interaction effects by the relatively small size of the dataset, these results suggest that the degree of contracting complementarity might be related to the marginal returns to system-to-system integration activities, a process which is more effectively conducted through coordinated in-house contracting.

Is the Degree of Governance Correlation Higher for Interdependent System “Pairs”?

We conclude our empirical analysis in Tables 5 and 6 with a more suggestive analysis which examines specific systems and the interrelationship among individual system “pairs.” To do so, we collapse our dataset to be composed of 19 observations (one for each car model) and examine the pairwise and conditional correlations across the systems at this level of aggregation. While the small size of our dataset precludes the use of an instrumental variables strategies, this more nuanced cut of the dataset allows us to assess whether the correlation in contracting practices is particularly high for those pairs where coordination investments are likely most important. The results are quite suggestive. Despite the small number of observations, some pairs where interactions are likely quite important (such as between the brake and suspension systems) are closely correlated with each other. On the other hand, where interactions are likely less important (such as between the suspension and electronic systems), the pairwise correlations are relatively low and the correlation is found to be negative after controlling for each of the other systems in Table 6. While we do not overemphasize these results as the correlation across specific systems is not identified separately from company-level factors, these results do suggest

²⁹ Do we need to describe these IVs a bit more here?

that our overall findings are consistent with a more fine-grained analysis of the relationship among vertical contracting decisions.

VII. Conclusions

This paper examined the impact of contracting complementarity across product development systems in the automobile industry. Building on a detailed qualitative understanding of the potential for interdependencies in contracting decisions, we tested this hypothesis using an instrumental variables approach that allowed us to distinguish contracting complementarity from firm-level factors inducing correlation among the firm's governance choices. Our empirical exploration uncovered a consistent pattern of support for the complementarity hypothesis. First, using instrumental variables to account for the endogeneity of the vertical integration choices for other systems within a model, the probability of vertical integration for each automobile system increases in share of other systems that are vertically integrated. Second, even when including system-specific measures of the contracting environment, the contracting environment associated with other systems has a significant impact on governance. Third, the degree of correlation in contracting is empirically related to measures which are likely associated with the marginal returns to system-to-system integration activities. Finally, though our dataset is not large enough to undertake a structural analysis of individual system-to-system "pairs," the degree of correlation seems to be highest for those "pairs" where the marginal returns to integration and coordination are likely most important.

While we interpret these findings cautiously, it is possible to draw out some implications from the analysis. First, our results suggest that assuming away contracting complementarity may be problematic in contexts where coordination and integration activities are both important and difficult to monitor. As emphasized by a number of "insider econometrics" studies (Ichniowski and Shaw, 2003), the elements of organizational design are interdependent and economic analysis of individual choices in isolation are likely to be biased. Second, the analysis suggests that empirical implications of contract theory can be derived even in the context of a model where there are no ex ante differences in the ability to write contracts but there are ex post differences in the ability to enforce and/or monitor agreements. In other words, our central hypothesis is a simple but novel implication of a model in which firms must make multiple interdependent contracting choices. Finally, the econometric framework offered by this paper

offers a refinement on prior research emphasizing the importance of choice-specific instruments in testing for complementarity in organizational design. Specifically, by collecting the data so that each choice-specific measure is observed in a symmetric fashion across choices, this paper proposes and implements a less ad-hoc instrumental variables test for complementarity in organizational design.

Our analysis also suggests several directions for further study. Perhaps most importantly, the current analysis highlights the consequences of an interaction between differences in the ex post contracting environment and the need for coordination and integration activities within the firm. While our theoretical discussion highlighted the potential importance of trade secrecy and co-location as a source of this interaction, our empirical work does not directly address the source of contracting complementarity. Our findings suggest that investigating the sources of the interaction between the nature of contracts and the incentives and investments required for coordination is a promising avenue. At the same time, research should also consider how concerns about the formal nature of contracts interact with potential for relational contracting, within and across firms over time. For contract theory to have empirical relevance, our theoretical structure must have implications for potential observables, and empirical research must be tailored to measure these subtle but observable factors.

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TABLE 1
Variables & Definitions.

VARIABLE	DEFINITION	MEAN	STD. DEV.
CONTRACTING VARIABLES			
VERTICAL INTEGRATION	Percentage of the system produced in house between 0 and 1 (1 indicates all in-house production)	.485	.324
VERTICAL INTEGRATION _{<i>i</i>}	Average level of VERTICAL INTEGRATION for all systems excepting <i>i</i> on model <i>j</i>	.485	.249
SYSTEM-SPECIFIC CONTRACTING ENVIRONMENT MEASURES			
SUNK COST	Dummy = 1 if pre-existing in-house sunk costs and/or plant investment for system <i>i</i>	.128	.335
LOW CAPACITY	Dummy = 1 if plant has insufficient capacity to manufacture system design in-house	.172	.378
PLATFORM	Dummy = 1 the component was designed to be used for more than one vehicle model	.526	.501
COMPLEXITY	Degree of System Complexity, ranging from 0 to 1 (See Novak and Eppinger, 2001).	.415	.272
UNION	Dummy = 1 if a component has been produced in-house and is covered under union agreement	.421	.496
VOLUME	Absolute company vehicle volume	2.889	1.978
SKILL SHORTAGE	Dummy = 1 if key worker skills are missing in existing plant locations	.150	.359
TECHNOLOGY	Dummy = 1 for the year in which substantial technological innovations are introduced	.113	.318
PERFORMANCE	Measure for desired performance goals at the system level, ranging from 0 (low) to 1 (high)	.449	.309
MAJOR	Dummy = 1 if the vehicle is undergoing a major change	.842	.366

Notes: VOLUME measured in millions.

TABLE 2
OLS Regressions.

Dependent Variable : VERTICAL INTEGRATION (N=133)				
	(2-1)	(2-2)	(2-3)	(2-4)
VERTICAL INTEGRATION _i	.862*** (.078)	.916*** (.058)	.699*** (.149)	.701*** (.155)
SUNK COST			.108 (.068)	.080 (.065)
LOW CAPACITY			-.145** (.060)	-.174** (.074)
PLATFORM				.007 (.039)
COMPLEXITY				.084 (.087)
UNION			.016 (.056)	-.011 (.063)
Ln (VOLUME)			.037 (.030)	.039 (.033)
SKILL SHORTAGE				.025 (.076)
TECHNOLOGY				-.021 (.059)
PERFORMANCE				-.144 (.095)
MAJOR				.004 (.060)
SYSTEM DUMMY VARIABLES				
SUSPENSION		.280*** (.059)	.226*** (.060)	.213*** (.078)
BRAKES		-.102 (.068)	-.175** (.079)	-.189** (.093)
TRANSMISSION		.181*** (.056)	.105* (.058)	.016 (.099)
ENGINE		.211*** (.046)	.105* (.059)	.126* (.072)
STEERING		.151** (.063)	.070 (.067)	.014 (.086)
BODY		-.145** (.063)	-.227*** (.068)	-.247*** (.072)
YEAR CONTROLS				
Year 2				-.005 (.050)
Year 3				-.044 (.048)
Constant	.067 (.042)	-.042 (.044)	-.402 (.396)	-.339 (.458)
R ²	.439	.660	.692	.702

Notes: Robust standard errors are given in parentheses. Stars denote statistical significance at 1 (***)
5 (**) and 10% (*) significance level.

TABLE 3
Vertical Integration IV Estimates

Dependent Variable : VERTICAL INTEGRATION (N=133)													
	(3-1)	(3-2)			(3-3)			(3-4)			(3-5)		
VERTICAL INTEGRATION _i	.918*** (.154)	1.123*** (.269)			1.227*** (.275)			1.242** (.566)			1.157*** (.243)		
SUNK COST	-.011 (.061)	.145* (.077)			.142* (.078)			.141* (.076)			.120* (.071)		
LOW CAPACITY	-.146*** (.055)	-.168** (.065)			-.168** (.070)			-.173** (.073)			-.191** (.080)		
PLATFORM					.045 (.044)			.050 (.047)			.038 (.043)		
COMPLEXITY					.104 (.087)			.106 (.085)			.138 (.092)		
UNION		-.059 (.078)			-.068 (.082)						-.081 (.080)		
Ln (VOLUME)		-.017 (.039)			-.030 (.040)						-.018 (.037)		
SKILL SHORTAGE TECHNOLOGY											.010 (.087)		
PERFORMANCE											.003 (.061)		
MAJOR											-.160 (.101)		
											.005 (.059)		
<i>Parametric Restrictions</i>		#Restr	F-stat	p-value	#Restr	F-stat	p-value	#Restr	F-stat	p-value	#Restr	F-stat	p-value
SYSTEM DUMMIES		6	11.01	.000	6	10.63	.000	6	8.66	.000	6	11.41	.000
YEAR CONTROLS		2	.01	.991	2	.07	.931	2	.18	.840	2	.21	.814
COMPANY DUMMIES								6	.19	.980			
Constant	.066 (.079)	.211 (.474)			.311 (.486)			-.035 (.121)			.255 (.483)		

Notes: Robust standard errors are given in parentheses. Stars denote statistical significance at 1 (***)
5 (**) and 10% (*) significance level.

Regressions (3-1) and (3-2): the instruments for VERTICAL INTEGRATION_i (VI_i) are the averages of SUNK COST and LOW CAPACITY across all systems but system *i*.

Regressions (3-3) and (3-4): the instruments for VI_i are the averages of SUNK COST, LOW CAPACITY, PLATFORM, and COMPLEXITY for all systems but system *i*.

Regression (3-5): the instruments for VI_i are those in (3-4) plus the averages of TECHNOLOGY, and PERFORMANCE, for all systems but system *i*.

TABLE 4
Reduced-Form Estimates

Dependent Variable : VERTICAL INTEGRATION		(N=133)			
	(4-1)	(4-2)	(4-3)		
SUNK COST	.027 (.067)	.013 (.080)	.134* (.076)		
LOW CAPACITY	-.338*** (.062)	-.362*** (.058)	-.374*** (.060)		
PLATFORM		-.009 (.055)	-.025 (.046)		
COMPLEXITY		-.078 (.089)	-.050 (.086)		
M_ SUNK COST _{-i}	.237 (.230)	.173 (.330)	.129 (.330)		
M_ LOW CAPACITY _{-i}	-1.270*** (.248)	-1.451*** (.231)	-1.374*** (.209)		
M_ PLATFORM _{-i}		-.400*** (.150)	-.400*** (.149)		
M_ COMPLEXITY _{-i}		-.871*** (.150)	-.832*** (.204)		
<i>Parametric Restrictions</i>			#Restr	F-Stat	p-value
SYSTEM DUMMIES			6	8.49	.000
YEAR CONTROLS			2	1.63	.200
Constant	.729*** (.068)	1.384*** (.109)	1.342*** (.122)		
R ²	.234	.419	.588		

Notes: Robust standard errors are given in parentheses. Stars denote statistical significance at 1 (***) , 5 (**) and 10% (*) significance level.

M_VARIABLE NAME_{-i} denotes the average of VARIABLE NAME across all systems but system *i*.

TABLE 5
Interaction Terms

Dependent Variable : VERTICAL INTEGRATION		(N=133)			
	(5-1)	(5-2)	(5-3)		
VERTICAL INTEGRATION _i	.720*** (.282)	1.173*** (.297)	1.292*** (.267)		
VL _i *PLATFORM	.692** (.292)	.454** (.209)	.257 (.195)		
VL _i *COMPLEXITY	-.427 (.449)	-.192 (.321)	-.437 (.306)		
VL _i *SKILL SHORTAGE		-.488** (.199)	-.408** (.166)		
VL _i *TECHNOLOGY		-.195 (.261)	-.012 (.210)		
VL _i *PERFORMANCE		-1.093** (.435)	-.716* (.375)		
SUNK COST	-.019 (.059)	.077 (.057)	.126** (.064)		
LOW CAPACITY	-.081 (.059)	-.023 (.067)	-.159** (.076)		
PLATFORM	-.275** (.135)	-.172 (.116)	-.102 (.101)		
COMPLEXITY	.232 (.211)	.087 (.181)	.283* (.171)		
UNION	.001 (.083)	-.037 (.085)	-.070 (.073)		
Ln (VOLUME)	.015 (.037)	.039 (.033)	.024 (.031)		
SKILL SHORTAGE		.074 (.119)	.217* (.116)		
TECHNOLOGY		-.008 (.120)	-.013 (.088)		
PERFORMANCE		.365* (.219)	.139 (.209)		
<i>Parametric Restrictions</i>			#Restr	F-stat	p-value
SYSTEM DUMMIES			6	10.58	.000
YEAR CONTROLS			2	.35	.705
Constant	-.106 (.461)	-.561 (.447)	-.402 (.462)		

Notes: Robust standard errors are given in parentheses. Stars denote statistical significance at 1 (***) , 5 (**) and 10% (*) significance level.

Regressions (5-1): the instruments for VL_i, VL_i*PLATFORM, and VL_i*COMPLEXITY are those used in regression (3-3) plus the second-order interactions of M_PLATFORM and M_COMPLEXITY with the instrumented interaction terms.

Regression (5-2) and (5-3): the instruments for VL_i and the interaction terms are those in regression (3-5) plus M_SKILL SHORTAGE, and the second-order interaction of these instruments (but M_CAPACITY) with the interaction terms.

TABLE 6: System-to-System Interactions – Correlations.

	VI_SUSP.	VI BRAKES	VI_TRANS.	VI_ENG.	VI_STEER.	VI_BODY	VI_ELECT.
VI_SUSPENSION	1.00						
VI_BRAKES	.88*	1.00					
VI_TRANSMISSION	.68*	.64*	1.00				
VI_ENGINE	.80*	.70*	.71*	1.00			
VI_STEERING	.58*	.53*	.66*	.83*	1.00		
VI_BODY	.33*	.19	.73*	.63*	.64*	1.00	
VI_ELECTRICAL	.59*	.59*	.87*	.81*	.80*	.82*	1.00

Note: A star denotes statistical significance at 5% significance level.

TABLE 7
System-to-System Interactions
Regressions of VERTICAL INTEGRATION in System *i* on
all each VERTICAL INTEGRATION component for Model *j*

	DEPENDENT VARIABLES						
	VI_SUSP.	VI BRAKE	VI_TRAN.	VI_ENG.	VI_ST.	VI_BODY	VI_ELEC.
VI_SUSPENSION		.723*** (.217)	.510* (.271)	.381* (.182)	-.063 (.470)	.120 (.284)	-.464 (.261)
VI BRAKES	.536** (.203)		.122 (.215)	.021 (.158)	-.124 (.322)	-.549*** (.172)	.392** (.132)
VI_TRANSMISSION	.335 (.197)	.108 (.178)		-.230 (.157)	-.062 (.336)	.265 (.182)	.364*** (.181)
VI_ENGINE	.813** (.315)	.061 (.438)	-.748* (.379)		1.074 (.802)	.359 (.417)	.426 (.454)
VI_STEERING	-.021 (.152)	-.056 (.141)	-.032 (.171)	.167 (.108)		-.050 (.150)	.157 (.133)
VI_BODY	.125 (.282)	-.773** (.274)	.421 (.257)	.176 (.261)	-.158 (.502)		.472** (.175)
VI_ELECTRICAL	-.533*** (.167)	.609* (.282)	.637*** (.202)	.229 (.199)	.543 (.559)	.519* (.241)	
Constant	.002 (.116)	-.246** (.110)	.274 (.169)	.234*** (.067)	-.158 (.231)	-.165 (.117)	-.093 (.121)
R ²	.888	.879	.857	.888	.745	.855	.924
N	19	19	19	19	19	19	19

Note: Robust standard errors are given in parentheses. Stars denote statistical significance at 1 (***), 5 (**) and 10% (*) significance level.

**Appendix A.
Pairwise Correlations**

	VERT INT	SUNK COST	LOW CAP	PLAT-FORM	LOW COMPL	UNION	VOLUME	SKILL SHORT	TECH	PERFOR-MANCE	MAJOR
VERTICAL											
INTEGRATION	1.00										
SUNK COST	-.01	1.00									
LOW CAPACITY	-.25*	.30*	1.00								
PLATFORM	.07	.05	-.00	1.00							
COMPLEXITY	-.15	.02	-.11	-.13	1.00						
UNION	.55*	.22*	-.15	.17	-.31*	1.00					
VOLUME	.73*	.08	-.16	.01	-.23*	.78*	1.00				
SKILL SHORTAGE	-.26*	.47*	.59*	.10	-.06	-.02	-.10	1.00			
TECHNOLOGY	-.22*	-.14	.15	.19*	-.09	-.11	-.10	.18*	1.00		
PERFORMANCE	-.13	-.14	-.17	-.10	.24*	-.23*	-.13	-.14	.09	1.00	
MAJOR	-.28*	-.14	.03	-.16	.32*	-.51*	-.27*	.01	.15	.18*	1.00

Note: A star denotes statistical significance at 5% significance level.