

DO MODULAR PRODUCTS LEAD TO MODULAR ORGANIZATIONS?

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The tacit assumption that increased product modularity is associated with advantageous increases in organizational modularity underlies much of the literature on modularity. Previous empirical investigations of this assumption, few in number, have faced numerous confounding factors and generated conflicting results. I build a causal model for the relationship between product and organizational modularity, which I test using a distinctive empirical setting that controls for confounding factors present in previous studies. I find support for only part of the assumed relationship, showing that modularity is a more multifaceted concept than previously recognized. In particular, increased product modularity enhances reconfigurability of organizations more quickly than it allows firms to move activities out of hierarchy. The paper contributes to the emerging stream of research that focuses on the previously underappreciated costs of designing and maintaining a modular organization. Copyright © 2006 John Wiley & Sons, Ltd.

INTRODUCTION

Sanchez and Mahoney (1996) articulated an assumption that underlies much of the recent work on the advantages of modularity: modularity in product design leads to modularity in organization design. Product modularity implies that changes in one component of the product do not require changes in other parts of the product. Similarly, organizational modularity implies that the various units involved in the product design process are loosely coupled, can operate autonomously, and can be easily reconfigured. As organizations become modular, 'a tightly integrated hierarchy is supplanted by a "loosely coupled" network of

organizational actors. The loosely coupled organizational forms allow organizational components to be flexibly recombined into a variety of configurations' (Schilling and Steensma, 2001: 1149; see also Orton and Weick, 1990).

Organizational modularity offers multiple advantages. Easier outsourcing allows firms to take advantage of capabilities beyond their boundaries (Baldwin and Clark, 1997; Fine, 1998). It allows firms to link together the capabilities of many organizations to support product development (Sanchez, 1995). The ease of reconfiguring the set of organizations involved in designing or producing a component allows a firm to select the best supplier for a given component at a given time (Garud and Kumaraswamy, 1995). This freedom allows the firm, in essence, to consider the outcomes of multiple experiments in how to design each component, increasing the expected value of the approach ultimately chosen (Baldwin and Clark, 2000; Langlois and Robertson, 1992). It also allows for 'modular innovation,' in which

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firms improve their end product by incorporating improvements in various components of the product, which may occur at different rates for different components (Langlois and Robertson, 1995: 301).

Because of these advantages, the theoretical and managerial literature has generally proceeded with the tacit assumption that firms with modular products will adopt modular organization forms.¹ Despite its impact, the asserted relationship between product and organizational modularity is supported by few explicitly causal models and even fewer empirical investigations (Schilling and Steensma, 2001). However, there are reasons to believe firms with modular products might not adopt modular organizational forms. For example, they might not perceive that the benefits of doing so outweigh the costs and risks (O'Sullivan, 2001). Or, they may not be able to overcome organizational inertia (Hannan and Freeman, 1989; Stinchcomb, 1965). Furthermore, some of the limited empirical evidence runs contrary to the dominant assumption (Brusoni and Prencipe, 2001; O'Sullivan, 2001).

This paper draws on transaction cost economics and the knowledge based theory of the firm to develop a causal model of the relationship between product and organizational modularity. It then uses a distinctive empirical setting to test the question 'Do modular products lead to modular organizations?' more cleanly than has been done previously. In particular, it controls for many confounding factors present in previous studies. Doing so reveals that the question was overly simplistic and that organizational modularity is a more multiplex phenomenon than previously recognized. I find support for only part of the assumed relationship. In particular, product modularity may not lead firms to move activities from hierarchy to more loosely coupled organizations to the degree that the literature has assumed. The results point to the need for more careful theoretical and empirical investigation of this heretofore generally accepted assumption, especially given its theoretical and managerial impact (e.g., Baldwin and Clark, 2000). They also contribute to an emerging stream of

research that focuses on the previously underappreciated costs of designing and maintaining a modular organization (e.g., Brusoni and Prencipe, 2001; O'Sullivan, 2001).

The paper proceeds as follows. The next section develops hypotheses on the relationship between product modularity and organizational modularity. I then review efforts to test this relationship, the challenges of doing so, and the ability of my empirical setting to overcome these challenges. Next, I discuss my empirical methodology. After a discussion of my results, a final section concludes.

THEORY AND HYPOTHESES

Mirroring any product design process is a corresponding organization design process. For example, designing a new notebook computer model requires the design of the computer as a whole and of components including the hard drive, display, and keyboard. The notebook manufacturer organizes the design process by choosing a supplier for each component and structuring the coordination between them. During the product design process, which may last many months, the suppliers will develop their respective components, the firm will develop the end product, and they will all work together so that the individual components integrate effectively in the end product.

One concern of the firm when organizing the production process will be to choose the supplier best able to produce each component. Transaction cost economics (Williamson, 1979) and the knowledge-based view of the firm (Grant, 1996) suggest other concerns. Transaction cost economics suggests that firms organize to minimize the risk of opportunistic behavior by the organizational units involved in the design process. The knowledge-based view suggests that firms organize to maximize the ease of communication—the transfer of knowledge—between the units involved in the product design process. These literatures also suggest strategies for achieving these goals and the resulting implications for the modularity of the firm's organization.

Getting the best component

To maximize the performance of the end product, it is in the interest of the firm to organize so that each component is produced in the best way possible

¹ As a measure of the prevalence of this assumption, 122 papers cite Sanchez and Mahoney (1996), while other influential studies (Baldwin and Clark, 2000: Ch. 14; e.g., Ulrich, 1995: 435) build on the same assumption, having reached it without direct reference to Sanchez and Mahoney.

(Pisano and Teece, 1989). Potential suppliers may differ in their technical capabilities and, thus, in their ability to produce a component according to the desired specifications and schedule. Firms develop their capabilities by carrying out related activities repeatedly (Nelson and Winter, 1982). Capabilities are often costly or impossible to transfer between organizations because they are difficult to articulate (Polanyi, 1962; Teece, 1981). Because of difference in past activities, potential suppliers have heterogeneous capabilities at any point in time.

Of course, firms can and do add capabilities, but because their development is a slow, uncertain and often costly process, it is 'rarely an attractive proposition to try and develop a collection of novel skills rapidly' (Teece *et al.*, 1994: 17). This suggests that firms organize production based on the *current* capabilities of potential suppliers (Henderson and Cockburn, 1994; Kamien and Schwartz, 1982).

If a potential supplier has superior capabilities to produce a desired component, the firm incurs opportunity costs if it does not take advantage of that supplier's capabilities. An alternative supplier either produces the component with its current inferior capabilities or must invest time and resources into building the needed capabilities. This leads directly to the first hypotheses:

Hypothesis 1: A buyer is more likely to select a supplier the greater that supplier's technical capabilities.

This hypothesis is highly plausible. However, it is important to establish the main effect of suppliers' technical capabilities as a baseline, as subsequent hypotheses will argue that modularity moderates firms' abilities to consider technical capabilities when choosing a supplier.

Moving from tight hierarchy to loosely coupled networks

Both the knowledge-based view of the firm and transaction cost economics suggest advantages for organizing production to use internal suppliers. Effective communication requires overcoming obstacles such as tacitness and social embeddedness (Szulanski, 1996; Ulrich, 1995). The ability of a firm to apply multiple mechanisms of knowledge transfer simultaneously and flexibly

within its boundaries maximizes the ease of doing so (Bird and Mitsuhashi, 2003). Kogut and Zander (1996) suggested that individuals' identification with the firm generates social knowledge that supports coordination and communication superior to that between firms. Communication routines and a common language for discussing technical issues arise more quickly within the firm because intra-firm communication is normally more frequent and intense than that with outsiders (Putterman, 1995). These advantages will be especially valuable in fast changing industries, where there is less time to build a deep understanding of a technology or to codify it (Hansen, 1999). Empirical evidence for the advantages of intra-firm communication includes Afuah's (2001) study of the impact of RISC technology on computer workstation manufacturers.

Transaction cost economics focuses on the risk of opportunism, which can include hold-up, below-the-market effort, or the misappropriation of proprietary information (Teece, 1977; Williamson, 1983). The firm can constrain opportunism within the firm through recourse to governance instruments that do not exist in external relationships (Williamson, 1985). These include managerial fiat; a greater legal burden on employees compared to contractors to disclose information (Masten, 1988); and judicial forbearance, which restricts access by employees to the courts to resolve internal disputes (Williamson, 1991). Fiat can efficiently, if not always optimally, resolve uncertainty about appropriate technological approaches, creating convergent expectations within the firm (Malmgren, 1961). Common ownership of various stages of production allows governance-related coordination difficulties to be resolved by fiat (Masten, 1984), allowing less complete contracts and less costly adaptation to unforeseen disturbances (Williamson, 1985).

Therefore, internal suppliers offer easier communication and lower risk of opportunism throughout the product design process. However, these advantages come at the cost of dampening high-powered incentives and incurring bureaucratic costs since firms cannot mimic the high-powered incentives of the market without added costs (Williamson, 1985: 140–153). As a result, internal suppliers are less attractive when the need to ease communication and constrain opportunism falls below a certain level. Therefore, I cannot make an unconditional prediction as to whether

a firm will organize production around internal or external suppliers.

However, I can predict that a firm will be more likely to include external suppliers given high product modularity. That is, they will move out of 'tightly integrated hierarchy,' which is one aspect of organizational modularity as described by Schilling and Steensma (2001) and others. This is because the advantages of internal suppliers become less important when the firm is designing a modular product since the process of designing a modular product makes communication less necessary and opportunism less likely.² Modularity allows for *information hiding* (Baldwin and Clark, 2000; Parnas, 1972), in which knowledge about the inner workings of one component need not be shared with the makers of other components. As a result, less communication is required during the product design process. Product modularity may reduce the risk of opportunism by making it easier to switch suppliers in the midst of the design process. In the case of a non-modular product, a firm will be loath to replace a supplier since changing suppliers for a component will almost certainly cause changes in the exact design of that component. The need to compensate for these changes in other components will disrupt the entire design process. As a result, the firm is vulnerable to hold-up by the supplier. By contrast, a firm may be able to replace a supplier as part of a modular design process more easily, since the resultant changes will not require significant changes in other components. A greater ability to change suppliers makes the firm less vulnerable to hold-up by a supplier:

Hypothesis 2: A firm will favor internal suppliers less when organizing to produce a modular product than when organizing to produce a systematic product.

Creating a reconfigurable organization

In addition to enabling a shift out of hierarchical structures, product modularity may enable a firm to reconfigure its supply chain easily, which is the second aspect of organizational modularity

² Of course, modularity is not a discrete concept. Components have varying degrees of modularity. However, when the components under discussion are far apart in their degree of modularity, it is convenient to refer to them as simply 'modular' and 'non-modular' or 'systematic,' as I do in this paper.

as described by Schilling and Steensma (2001). That is, it may allow a firm to add new suppliers and drop existing suppliers while creating minimal disruption throughout the design process. This is despite the advantages that both the knowledge-based view and transaction cost economics indicate a firm gains by working with the same suppliers over an extended period, that is, by *not* reconfiguring their supply chain.

Over extended periods of interaction, a firm and its supplier can develop many, but not all, of the communication advantages that exist within the firm. They can develop communication routines that span the partner organizations (Nelson and Winter, 1982). They will likely also develop a common language to discuss technical issues (Buckley and Casson, 1976). This is particularly important for uncoded knowledge, which is especially likely to be important when designing a new product (Arrow, 1974).

Governance is also eased as a buyer and supplier interact over time. Expectations for future opportunistic behavior are lower for a partner that has refrained from opportunistic behavior in the past (Crocker and Reynolds, 1993). Past behavior can thus increase trust between contracting partners, where trust is defined as 'a type of expectation that alleviates the fear that one's exchange partner will act opportunistically' (Bradach and Eccles, 1989: 104). The importance of *repeated* interaction in developing trust is one of the strongest findings common to studies of trust (Gulati, 1995; Shapiro, Sheppard, and Cheraskin, 1992). Easier communication and higher trust create efficiencies for both parties, which serve as a brake on opportunism (Williamson, 1983). So long as the benefit of opportunism does not exceed the value of the relationship, neither party is likely to risk the long-term value of the relationship for short-term gain, either by blatant acts of opportunism such as breach of contract or more subtle actions such as below-peak performance (Klein, 1980; Pisano, 1989).

Empirically, Parkhe (1993) found that a prior history of cooperation between two firms reduced their expectation of opportunism. Heide and Miner (1992) found that buyer-supplier cooperation increased with a higher frequency of contact in the existing relationship. Gulati (1995) found that trust was greater among partners that had transacted in the past.

However, long-term relationships may also incur the cost of diminished incentives. Parties in long-term relationships may give second chances more frequently, expect due process before termination, and be more willing to negotiate unexpected cost increases. For example, Uzzi (1997: 43) quotes a contractor as saying 'With people you trust, you know that if you have a problem with a fabric they're just not going to say, "I won't pay" or "take it back". If they did then we would have to pay for the loss.'

These costs make it impossible to make an unconditional prediction as to how much a firm will value prior relationships when organizing production. However, I can predict that firms will value prior relationships more for systemic products than modular products. This is because past relationships between a firm and a supplier become increasingly irrelevant as the product becomes more modular. Modularity lowers the need to ease communication and constrain opportunism. In the case of modular products, component producers do not need information about the inner workings of other components (Baldwin and Clark, 2000). This means less need for communication during the design process. Product modularity may also reduce a firm's vulnerability to hold-up by a supplier by making it easier to replace the supplier of a given component during the design process. A new supplier may mean changes in the detailed specifications of that component. However, modularity means these changes will not require significant changes in other components. In sum, modularity means that a firm gives up fewer relevant advantages by switching to a new supplier. Thus, modularity allows a firm to reconfigure its supply chain more easily:

Hypotheses 3: A firm will value prior transactions with a supplier more when organizing to produce a systemic product than when organizing to produce a modular product.

Summary

In the absence of modularity, transaction cost economics and the knowledge-based view of the firm both suggest that firms will organize their production around long-term and internal suppliers to maximize ease of communication and minimize the risk of opportunism. Firms and their suppliers will be tightly coupled and a firm will rarely

reconfigure its supply chain. However, these theories also suggest that the advantages of long-term and internal suppliers become less important in the presence of product modularity. Firms can move activities out of hierarchy (Hypothesis 2) and reconfigure their supply chain (Hypothesis 3). While organizing to include the most technically capable suppliers in the product design process is always desirable (Hypothesis 1), product modularity allows firms to give greater weight to technical criteria when choosing suppliers. In short, product modularity is predicted to lead to organizational modularity.

EMPIRICAL TESTING: CHALLENGES AND UNIQUE SOLUTIONS

Challenges

It has been difficult to test the relationship between product and organizational modularity because we rarely observe product design processes that differ in their degree of modularity, but not along other dimensions. Many enlightening studies have examined examples of product designs, e.g., the Sony Walkman, that are modular and appear to be embedded in modular networks of suppliers (Sanchez and Mahoney, 1996, provide an inventory; see also Schilling, 2000). However, without a counter-example, e.g., a non-modular Sony Walkman, it is difficult to determine the actual impact of product modularity on organizational modularity.

Given this challenge, it is not surprising that the existing empirical evidence is mixed. Schilling and Steensma (2001) found evidence that modular product designs, particularly the availability of standards, were associated with more modular organizational forms at the industry level. At the firm level, Baldwin and Clark's (2000) examination of increasing modularity in the computer industry, particularly the development of IBM's System/360, provided evidence for the impact of increasing product modularity on organizational modularity. While the longitudinal nature of their study provided clear evidence that changes in product modularity were correlated with changes in organizational forms, it may also have masked the impact of other changes such as developments in related technologies, shifts in the institutional environment, and changes in the identity and capabilities of potential suppliers.

In contrast to these results, Brusoni and Principe's (2001) case studies of the aircraft engine and chemical engineering industries found that modular product architectures actually required highly interactive organizational set-ups to provide the information structure necessary to coordinate the various organizational units involved in production. As a result, they warn against assuming a one-to-one mapping between product and organizational modularity. Hsuan (1999) found that even in supposedly modular products, firms often found close, enduring relationships with their suppliers more beneficial than short term relationships.

Unique solutions

I observe the organizational design choices made by notebook computer makers when designing a computer that will use an innovative flat panel display. Unlike previous studies, this setting allows me the luxury of observing product design processes that differ in their degree of modularity, but not along other dimensions. For technological reasons detailed below, a notebook incorporating a larger display is systemic, while a notebook incorporating a higher-resolution display is modular. I observe decisions regarding both cases. All of the decisions took place in the same period, 1992–98, and involve the same buyers, suppliers, and basic technology. I am therefore able to control for potential confounding factors including unobserved heterogeneity between firms, shifts in the institutional environment over time, variation in the identity and capabilities of potential suppliers, and differences in the underlying technology. This allows me to isolate the impact of product modularity on organizational modularity in a way previous studies have not.

Displays are a key component in notebook computers because they are a large part of the user experience. To distinguish their products, notebook computer manufacturers have sought to design new models that incorporate innovative displays. Because of competitive pressures, computer firms cannot wait for an innovative display to exist before beginning to design the computer into which it will be integrated. The race to introduce a notebook with a 14-inch display was underway when the largest available notebook display was 13 inches.

In fact, notebook manufacturers were typically running two simultaneous races: one to incorporate larger displays and another to incorporate improved resolution displays at existing sizes. For example, when the leading-edge display was a 13-inch VGA, manufacturers were seeking both a 13-inch XGA display and a 14-inch display of whatever resolution was initially possible at that size. Either would lead to a more attractive notebook computer. Since the challenges to be overcome in both the display and notebook differed for the 13-inch XGA and the 14-inch display, these were separate design processes and could involve different suppliers.

Over a 9- to 18-month design process the notebook manufacturer will design the notebook, while the display supplier develops the new display. The process requires continuous communication between notebook maker and display supplier, partially because so many of the parameters in question are subjective. For example, although it is possible to specify and measure a display's absolute brightness, designers can determine consumer acceptance of a given brightness only in the context of other parameters, including color matching, brightness uniformity and brightness leakage.

As a result, even though the initial specifications from the notebook manufacturer are usually very demanding, the manufacturer and supplier will negotiate compromises during development on a wide spectrum of specifications including driving method, driving voltage, input signal, the dimension of the module, and connector shapes. This product design process poses the communication and governance challenges that are the focus of this paper. Furthermore, the competitive significance of producing models with advanced displays ensures that the organizational design decisions I observe reflect careful consideration on the part of notebook computer manufacturers.

Advances in notebook computer displays have focused on two dimensions: size and resolution. The appeal of a larger display is obvious: the user can view more information on the display. Resolution measures the number of pixels on the display. A pixel is the smallest element the display can show. The more pixels, the more information displayed. Within a given size display, higher-resolution displays have smaller pixels, allowing a finer-grained display. This taxes the eyes less and is required for any sort of multimedia application.

Increasing display size and increasing resolution both present numerous technical challenges. Larger displays require new handling equipment and new processes. For example, it becomes necessary to apply vapor deposition and photolithography uniformly over an ever-increasing surface area. Increasing resolution requires putting more circuitry on the same size display. This requires reduced line-widths, tighter tolerances, and more driver chips with more challenging packaging.

In addition to developing the new display, the notebook manufacturer and supplier must work together to integrate the new display with the rest of the computer. Size increases are more difficult to integrate. The most obvious challenge is making the notebook computer case large enough to hold the display while keeping it compact and durable. This is far from trivial. The seemingly lowly hinge between the top and bottom portions of a notebook computer is often a critical engineering factor. Since most people close their computer by grabbing an upper corner of the panel, there is enormous torque on the hinges and the display. Larger displays are effectively longer levers, which create greater torque. Thus, this problem becomes more severe as display size increases, which was a major reason that displays with 16.5-inch and 17-inch displays languished at the prototype stage for an extended period.

Another concern is protecting the glass from breakage. A substantial portion of the early design process focuses on the ability to design a notebook with a given display that can pass the drop test (repeatedly dropping the notebook to test its ability to protect the display from damage when dropped). Doing so involves not only the design of the display, but also the entire case, and becomes increasingly difficult as display size increases.

Larger displays also draw more power, rapidly depleting batteries. Providing acceptable battery life requires changing the computer's power management system, including the battery, related hardware and software, and charging system. Compensating changes will be necessary in other components of the notebook that draw power, including the hard disk, CD-ROM or DVD drives, and speakers.

Because of this extensive set of interactions, a notebook incorporating a larger display is very systemic, i.e., non-modular, in its design. By contrast, the challenge of increasing resolution is mostly contained within the display and interacts less with

the design of the rest of the computer. A notebook incorporating a higher-resolution display is therefore more modular.³

DATA AND METHOD

To test my hypotheses, I carried out a quantitative study of notebook computer manufacturers' organization design decisions from 1992–1998. Interviews at three notebook computer manufacturers in the United States and Japan, two of which also produced displays, and with other industry participants supplemented the quantitative study. Interviews at the notebook manufacturers were semi-structured. In order to assure maximum clarity during the interviews in Japan, I began with a pre-translated set of questions in Japanese. Depending on the language ability of the respondent, responses and further questions took place in Japanese, English, or a combination.

My primary data source for the quantitative study was the COMTRAK database compiled from 1992–1998 by Stanford Resources, one of the industry's leading consulting firms. For each model produced by 13 notebook manufacturers, the database provided the size and resolution of the display, as well as the firm that supplied it. Stanford Resources compiled the information in COMTRAK from interviews with display suppliers and notebook manufacturers. Stanford Resources had a strong incentive to be as complete and accurate as possible in compiling this data; COMTRAK subscribers paid approximately \$1250 per quarterly issue and were well-informed participants in the industry. COMTRAK allowed me to compile a complete inventory of a notebook manufacturer's relationships with display suppliers. The data include 116 instances in which a notebook manufacturer introduced a model with a larger or higher-resolution display than they had previously

³ This distinction was particularly salient for the period covered by my data (1992–98) since the interactions between buyers and suppliers during this period were much greater for the incorporation of size increases than for resolution increases. Prior to 1998, there were no set standards for physical design, thus, requiring substantial interactions and systemic changes when adapting to the physical differences between display sizes. Further, prior to 1998, the move to super-high-resolution displays (SXGA and UXGA) had not yet occurred, so there was not as much need for interaction while making resolution increases. (The levels of electromagnetic interference were not as significant for the lower resolutions that were state of the art at that time.)

offered. These improvements occur in discrete steps. For example, a manufacturer might move from a 12.1-inch display to a 13.3-inch display. Or, it might move from a 12.1-inch XGA display to a higher-resolution 12.1-inch SXGA display. Each such increase represents a separate innovation for which the manufacturer must select a supplier and engage in design work to incorporate.

There is only one case of exit: Texas Instruments left the notebook computer business in 1997. I augmented this data with the trade press and issues of *Laptop Handbook and Buyer's Guide*. Valuable information on the industry's development came from Murtha, Lenway, and Hart (2001).

For each notebook in which a manufacturer integrated an innovative display, I generated an observation for each potential display supplier, including measures of the supplier's technical capabilities and the characteristics of the manufacturer–supplier relationship at that time, a vector of control variables, and an indicator of whether the manufacturer selected that supplier for its initial introduction of the innovation.

Table 1 summarizes my conceptual variables and the empirical data used to test them. Table 2 presents descriptive statistics and correlations.

Dependent variable

In the set of observations related to a manufacturer's introduction of a given innovation, this indicator variable was set to 0 for all suppliers except the one the manufacturer chose. For that supplier, it was set to 1.

Independent variables and measures

Technical capabilities

Patents are a widely used measure of technical capability (Hall, Jaffe, and Trajtenberg, 2000). I measure a supplier's technical capability by the number of its display-related U.S. patents over the last 5 years, PATENTS. An industry informant confirmed that, although decision-makers rarely if ever actually count the number of display-related patents each potential supplier holds at a given time, the number of patents a supplier held by a supplier correlates closely with its research activity, technical capabilities, and with other firms' beliefs about those capabilities. I defined display-related patents as those containing the terms 'liquid crystal display' or 'LCD' or classified in International Patent Classification (IPC) section G02F 1/–, G09G 3/–, G09F 9/3–, or G09F 13/–. These patent classifications were selected according to Spencer (1997). I then confirmed that they were the classifications common to all patents selected for inclusion in the 'Liquid Crystal Display' section of *Industry and Technology Patents Profiles: Electronic Displays and Display Applications*, published by Derwent Information/Thompson Scientific, a leading publisher of patent information. I have no *a priori* assumptions of how quickly the value of knowledge depreciates in this industry, so I also tested my models using display-related patents in the immediately previous year and total display-related patents. The results are robust.

Table 1. Conceptual variables and corresponding empirical data

Conceptual variable	Empirical data	Variable name
<i>Independent variables</i>		
Technical capability of supplier	Number of U.S. display-related patents in previous 5 years	PATENTS
Nature of manufacturer–supplier relationship	Number of years in which manufacturer and supplier have transacted	PAST RELATIONSHIP (YEARS)
Nature of manufacturer–supplier relationship	Number of manufacturer's notebook models for which supplier provided displays	PAST RELATIONSHIP (MODELS)
Nature of manufacturer–supplier relationship	Are the manufacturer and supplier part of the same company (0/1)	INTERNAL SUPPLIER
Control variable	To what degree do the manufacturer and supplier compete in the notebook market	COMPETITOR
Control variable	Are the manufacturer and supplier of the same nationality (0/1)	SAME NATIONALITY
<i>Dependent variable</i>		
Choice of supplier	Is this the supplier actually selected for the given innovation (0/1)	CHOICE

Table 2. Descriptive statistics and correlations

Modular products (incorporating higher-resolution displays)

	Mean	S.D.	Min.	Max.	1	2	3	4	5	6	7
1 CHOICE	0.03	0.17	0.00	1.00	1.00						
2 SAME NATIONALITY	0.41	0.49	0.00	1.00	0.01	1.00					
3 PATENTS	175.20	195.80	0.00	834.00	0.22*	-0.01	1.00				
4 PAST RELATIONSHIP (MODELS)	1.14	5.00	0.00	48.00	0.27*	0.05	0.30*	1.00			
5 PAST RELATIONSHIP (YEARS)	0.23	0.69	0.00	4.00	0.31*	0.00	0.34*	0.83*	1.00		
6 INTERNAL SUPPLIER	0.04	0.20	0.00	1.00	0.26*	0.23*	0.10*	0.40*	0.33*	1.00	
7 COMPETITOR	9.33	7.48	0.00	31.30	-0.09*	-0.08	0.20*	-0.08	-0.10*	-0.25*	1.00

* Indicates significance at 0.10 level; 33 decisions, yielding 1056 observations.

Systemic products (incorporating larger displays)

	Mean	S.D.	Min	Max	1	2	3	4	5	6	7
1 CHOICE	0.03	0.17	0.0	1.00	1.00						
2 SAME NATIONALITY	0.40	0.49	0.0	1.00	-0.03	1.00					
3 PATENTS	187.48	205.10	0.0	926.00	0.24*	-0.08*	1.00				
4 PAST RELATIONSHIP (MODELS)	1.29	5.19	0.0	49.00	0.32*	0.01	0.32*	1.00			
5 PAST RELATIONSHIP (YEARS)	0.27	0.77	0.0	5.00	0.34*	-0.06	0.37*	0.83*	1.00		
6 INTERNAL SUPPLIER	0.04	0.20	0.0	1.00	0.19*	0.23*	0.11*	0.33*	0.24*	1.00	
7 COMPETITOR	8.76	7.34	0.0	34.40	-0.08*	-0.05	0.21*	-0.06	-0.08*	-0.25*	1.00

* Indicates significance at 0.10 level; 35 decisions, yielding 1120 observations.

The manufacturer-supplier relationship

I measure two aspects of the relationship between the manufacturer and each of its potential suppliers: the degree to which they have transacted in the past and whether they belong to the same company.

The first measure of past transactions is the number of previous years in which the manufacturer has purchased at least one notebook computer display from the supplier, PAST RELATIONSHIP (YEARS). To capture the intensity of the past relationship, I also measure past transactions using the total number of different notebook computer models for which the given supplier supplied displays to the manufacturer, PAST RELATIONSHIP (MODELS). To the degree that a buyer and supplier had transacted prior to their entry into my data, my measure of their relationship will be truncated. To control for this, I do not model decisions made in the first three years of a buyer being

present in the data. Sixty-eight model introductions remained, 33 involving higher-resolution displays (modular) and 35 involving larger displays (systematic).

The indicator variable, INTERNAL SUPPLIER, is set to 1 if the supplier is part of the same company as the notebook manufacturer. The value of previous transactions may differ for internal and external suppliers. For example, if hierarchical controls reduce the impact of trust, each year of experience would provide less benefit for internal suppliers. Therefore, I include the interaction of INTERNAL SUPPLIER and the two measures of past relationship.

Control variables

Working with a supplier from another country creates several challenges, including language differences (Arrow, 1971) and, possibly, lower trust

(Zucker, 1986). These effects may have diminished given the pervasive globalization of the electronics industry, but I include an indicator variable, SAME NATIONALITY, set to one if the supplier is of the same nationality as the manufacturer, to control for possible effects.

Some notebook manufacturers and potential suppliers had inter-organizational relationships in other fields. For example, Acer and Texas Instruments had a joint venture to manufacture memory chips starting in 1989. These relationships might generate trust and communications ability between the firms. To control for the effect of these relationships, I use the Quadratic Assignment Procedure (QAP) from network analysis, as described in the Appendix. This procedure controls for the unobserved heterogeneity in buyer–supplier dyads, including unobserved relationships.⁴

Firms occasionally procure displays from suppliers with which they compete in the notebook computer market, despite the possibility of information leakage and opportunistic behavior in the display market to influence competition in the notebook market. Industry informants suggest that the high minimum efficient scale and significant cycles of supply–demand imbalance in the display industry drive this behavior. Downstream competitors rely on cross-selling of displays to even out these imbalances. Reputation effects mean that a blatantly opportunistic supplier would be unable to sell to downstream competitors in the future, a powerful incentive to avoid opportunistic behavior. Since the impact of a potential supplier being a competitor in the notebook market is unclear, I include a variable (COMPETITOR) measuring the intensity of competition between the buyer and supplier in the notebook computer market. If the supplier does not produce notebook computers, this variable is set to 0. Otherwise, it is set to the sum of the manufacturer and supplier's worldwide market share in the notebook computer industry.⁵

⁴ An extensive literature review identified some of these relationships. However, many relevant relationships, such as purchases of other components from a supplier, never appear in the press and the nature of these relationships varied enormously. There is no theoretical basis for rating these relationships on a continuous basis and a dichotomous variable is not appropriate. Fortunately, QAP controls for their effect, although it does not allow me to measure their impact.

⁵ As is usually the case, I lack information on the price offered by each supplier. However, my interest is in the *comparing* organization design decisions for modular and systemic products.

The discrete choice model

For each innovation, manufacturers chose one supplier from the pool of all potential suppliers. I therefore apply a logit model, specifically McFadden's (1973) discrete choice model, which assumes that manufacturers choose the supplier that provides the highest level of utility, where utility is an unobservable, latent variable. Let the potential suppliers be indexed by s and the manufacturers making the choice by m . The vector of variables associated with supplier s at the time a supplier was being chosen for innovation i is \mathbf{x}_{si} and the vector of coefficients to be estimated be given as β . The utility a manufacturer obtains by choosing supplier s is

$$U_{si} = \beta' \mathbf{x}_{si} + \varepsilon_{si} \quad (1)$$

where the error term, ε_{si} , is an unobserved random term that is an identically and independently distributed extreme value, independent of β and \mathbf{x}_{si} , reflecting unobserved heterogeneity in decision making, that is, the impact of unobserved factors, differences in tastes, and imperfect judgment on manufacturers' decisions.

The probability of manufacturer m choosing supplier s for innovation i is given as

$$P(y_{mi} = s | \mathbf{x}_{si}) = \frac{\exp(\mathbf{x}_{si} \beta)}{\sum_{j=1}^s \exp(\mathbf{x}_{ji} \beta)} \quad (2)$$

In considering modeling strategies, it is useful to note that because utility is an unobservable, latent variable, it is not possible to estimate its variance, σ^2 , and the coefficients, β , have no natural scale (Long, 1997: 47; Maddala, 1983: 23). We are limited to arbitrarily setting σ to mathematically convenient value and estimating $\beta = \alpha/\sigma$, where α is the 'true' effect of the covariate.

My hypotheses focus on whether manufacturers are more likely to choose long-term or internal suppliers for a systematic product than for a modular product. Testing my hypotheses requires comparing the statistical significance and relative magnitude of the relevant covariates for modular and systemic products. There are several statistical approaches to making such a comparison.

There is no reason to suspect that price would have a stronger impact on one class of design than another.

One approach is to estimate a single regression for all innovations (Aiken and West, 1991). A dummy variable is set to 1 for one type of innovation, e.g., systemic, and interacted with the relevant covariates. Considering only one variable, x , and letting the dummy variable, S , be set to 1 for systemic innovations, the equation would be of the form

$$Y_i = \beta_0 + \beta_1 x_i + \beta_2 (S_i x_i) + \varepsilon_i \quad (3)$$

An estimate of β_2 significantly different than 0 indicates that the impact of x varies between modular and systemic innovations. The sign of β_2 indicates whether the impact of x is diminished or increased for systemic innovations.

As indicated by the presence of a single error term, ε_i , this approach assumes that the error variance, σ^2 (that is, the amount of unobserved heterogeneity), is the same for modular and systemic innovations (Darnell, 1994: 111; Pindyck and Rubinfeld, 1991: 107). The likely effect of using a single equation despite differences in variance between the groups is that the slope coefficients will *not* be found to be different, even if they actually differ (Gujarati, 1988: 527). In the logit case, significant results with the wrong sign may even result (Hoetker, 2004). Since estimation of a logit model requires arbitrarily setting the value of σ , it is not possible to test the assertion that two groups have the same error variance.

Unfortunately, unobserved heterogeneity between modular and systemic innovations likely differs. Modular innovations require less management over the design process, reducing the cost of choosing a hard-to-manage supplier. This fact may give more play to unobserved factors such as personal preference and convenience and cause managers simply to pay less attention in their decision making, leading to more errors of judgment. Either circumstance would increase the heterogeneity of decisions regarding modular innovations. Although untestable, this logic casts severe doubt on the results that combining systemic and modular innovations into a single estimation would generate.

Therefore, I estimate modular and systemic innovations in separate regressions. This avoids the unsupportable assumption of common variance at the cost of complicating comparisons of the effect of covariates across innovation types.

Since there were 32 potential suppliers for each of the 68 new model introductions, this yielded $68 \times 32 = 2176$ observations. Hausman and McFadden's (1984) test indicates that my sample exhibits independence of irrelevant alternatives, an assumption of the discrete choice model. To control for possible autocorrelation caused by unobserved characteristics of buyers, I used robust standard errors, clustered by notebook manufacturer (Rogers, 1993).

RESULTS

Table 3 presents my quantitative results. In each model, the observations are divided into modular (resolution increases) and systemic (size increases) products. Model 1 measures the past relationship between the notebook manufacturer and display supplier by the number of years in which they have transacted, PAST RELATIONSHIP (YEARS). Model 2 measures the relationship by the number of the notebook manufacturer's past models that used displays from the supplier, PAST RELATIONSHIP (MODELS). Ramsey's RESET test reveals no evidence of misspecification or omitted variables (Peters, 2000; Ramsey, 1969).

In both models, PATENTS is positive and highly significant for both modular and systemic products, indicating that the more display-related patents a supplier has, the greater the likelihood that the manufacturer will chose it. This confirms the importance of capabilities, as predicted in Hypothesis 1. In their quest for timely, successful development of displays, notebook computer manufacturers value suppliers' technical capabilities regardless of the model's degree of modularity.

Contrary to predictions, modularity does not help firms move activities out of hierarchy as predicted in Hypothesis 2. A significant result for systemic products and a non-significant result for modular products would have provided evidence for Hypothesis 2. However, in both Models 1 and 2, firms prefer internal suppliers for both systemic and modular products ($p < 0.01$ in all cases). Beyond the patterns suggested by statistical significance, we can directly estimate the relative strength of firms' preference for internal suppliers for modular and systemic designs. Because the coefficients in any logit equation are scaled by an unknown variance, it is not possible

Table 3. Results of discrete choice models of supplier selection

Hypothesis	(1)		(2)	
	Systemic	Modular	Systemic	Modular
H1	SAME NATIONALITY		−1.146*	−1.053
			(0.765)	(0.660)
	COMPETITOR		−0.091**	−0.048
			(0.041)	(0.035)
H2	PATENTS		0.004***	0.005***
			(0.001)	(0.001)
H2	INTERNAL SUPPLIER		1.932***	2.803***
			(0.950)	(0.505)
H3	PAST RELATIONSHIP (YEARS)		0.686***	0.367
			(0.250)	(0.431)
H3	INTERNAL SUPPLIER * PAST RELATIONSHIP (YEARS)		−0.309	0.379
			(0.423)	(0.716)
	PAST RELATIONSHIP (MODELS)		0.069*	0.012
			(0.045)	(0.045)
	INTERNAL SUPPLIER * PAST RELATIONSHIP (MODELS)		0.069	0.012
			(0.054)	(0.061)
Log-likelihood		−75.93	−78.98	−76.88
Decisions observed		35	35	33
Observations		1120	1120	1056

Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1% (one-tailed tests for hypotheses; two-tailed tests for control variables).

Modular, display had increased in resolution; Systemic = display had increased in size.

to compare coefficients across samples (Allison, 1999; Swait and Louviere, 1993). However, it is valid to compare ratios of coefficients.⁶ Further, this ratio has a straightforward interpretation as the rate at which manufacturers will trade one factor for another (Boskin, 1974; Maddala, 1983; Train, 2004: 43). For example, the ratio $\beta_{\text{internal}}/\beta_{\text{patents}}$ indicates the value of working with an internal supplier relative to the value of each patent a supplier has. If Hypothesis 2 were correct, this value would be less for modular designs than systemic designs since hierarchy is hypothesized to provide more valuable benefits for systemic designs.

In Model 1, this calculation yields a value of 564.6 for systemic designs. That is, firms value working with an internal supplier as much as they

value a supplier having 565 patents. The same calculation for modular designs yields a value of 447.2. If this difference were statistically significant, it would mean that the advantages of working with an internal supplier are worth less for modular designs, as predicted. However, it is far from statistically significant ($p = 0.63$). The same calculations in Model 2 yield substantively similar results: the value of working with an internal supplier is statistically indistinguishable for modular and systemic designs.

Hypothesis 3, in contrast, is supported. In Model 1, prior transactions, measured by duration, are positive and significant ($p < 0.01$) for systemic designs. Prior transactions are insignificant ($p = 0.197$) for modular designs. Because modular product designs make the benefits of prior transactions much less important, firms are able to reconfigure their supply chains for modular products more freely than they can for systemic products. Model 2, which measures prior transactions by the number of models for which a buyer had purchased displays from a supplier, gives the same result. Prior transactions are positive and significant for systemic designs ($p < 0.1$) and insignificant ($p = 0.392$) for modular designs.

⁶ Recall that the estimated coefficient β is the true effect of the covariate, α , scaled by the standard deviation of the error term, σ , $\beta = \alpha/\sigma$. When we arbitrarily set σ , we also arbitrarily set the scale of β . Accordingly, if σ varies between groups, the estimated β coefficients will also vary, even if the true effect of the covariate, α , is the same across groups. However, if we take the ratio of two coefficients, we find that $\beta_2/\beta_1 = (\alpha_2/\sigma)/(\alpha_1/\sigma) = \alpha_2/\sigma(\sigma/\alpha_1) = \alpha_2/\alpha_1$. By taking a ratio, we have removed the impact of the error term and are left with a ratio of the true effects of x_1 and x_2 . We can compare this ratio across groups, since it is no longer confounded by differences in unobserved heterogeneity.

Calculating the relative value of prior transactions for systemic and modular products provides even stronger evidence for the impact of modularity. Calculating $\beta_{\text{models}}/\beta_{\text{patents}}$ in Model 2 shows that each model for which a supplier has supplied a display is as valuable as 17.9 patents for a systemic design, but only 2.5 patents for a modular design. Prior transactions are less than one-seventh as important for modular designs as for systemic designs, a statistically significant difference ($p < 0.05$).

An example illustrates the implied impact of product modularity on the reconfigurability of a firm's supply chain. Assume a manufacturer has previously purchased displays for 10 models from a supplier. For its next model, it is choosing between its current supplier and a new supplier with 100 more patents. For a systemic product, while the capabilities of the new supplier are attractive, the communication and governance required to manage the design process are great enough that the experience with the current supplier is more valuable. The manufacturer will not reconfigure its supply chain even to take advantage of the technically superior supplier. For a modular product, however, the need for communication and governance is low and the additional technical capabilities more than offset the lack of prior experience. The manufacturer will reconfigure its supply chain to use the new supplier.

Results for the two control variables contain no surprises. SAME NATIONALITY is significant only for systemic designs in Model 2, where it is negative, indicating that firms are less likely to choose suppliers from their own country. This is likely an artifact of the data. The majority of observations are by U.S. manufacturers, and there are few U.S. suppliers available. If more Japanese manufacturers were in the data, their tendency to purchase from Japanese suppliers (including internal suppliers) would very likely render this coefficient insignificant or even positive.

In both models, COMPETITOR is negative and significant for systemic designs, but insignificant for modular designs, indicating that downstream competition inhibited a firm from choosing a supplier for systemic, but not modular designs. This is theoretically consistent. Modularity reduces the risk of opportunism by making it easier to switch suppliers in the midst of the design process. The assembler is less vulnerable to opportunistic

actions a supplier might make to affect competition in the notebook market and therefore less averse to purchasing displays from a supplier-cum-competitor (Hoetker, Swaminathan, and Mitchell, 2002 find evidence of this effect in the automotive supply industry).

In summary, the results strongly support Hypotheses 1 and 3. Firms always value the technical capabilities of suppliers, and product modularity allows firms to reconfigure their organizations more freely. Hypothesis 2 is not supported. Product modularity does not appear to induce firms to move activities out of hierarchy.

DISCUSSION

This paper draws on the knowledge-based view of the firm and transaction cost economics to build a causal model for the relationship between product and organizational modularity. It then uses a distinctive empirical setting to test the question 'Do modular products lead to modular organizations?' more cleanly than has been done previously. In particular, it controls for many sources of variation that other studies have not. Doing so reveals that the question was overly simplistic. Modular products lead to more reconfigurable organizations, part of the common definition of modular organizations. However, product modularity contributes less or not at all to another important part of organizational modularity, firms shifting activity out of hierarchy. The paper's three main contributions come from these findings.

The first contribution is to provide empirical evidence for the impact of product modularity on the ease with which a firm can reconfigure its organizational design. Despite the general acceptance of this impact, little empirical evidence exists for it (Schilling and Steensma, 2001) and the evidence that does exist is mixed (Brusoni and Prencipe, 2001). Since much of the theoretical and managerial literature takes this relationship for granted, the rigorous test provided by this paper is valuable confirmation.

The second and third contributions come from the surprising finding that product modularity did not help firms move activities out of hierarchy, in contrast to the findings of Baldwin and Clark (2000) and others. It is possible, of course, that the difference in modularity observed in this study was insufficient to enable firms to move activities

out of hierarchy. Perhaps we would observe the move out of hierarchy if the product design were even more modular. Importantly, however, the process of integrating higher-resolution displays was sufficiently modular to allow firms to reconfigure their supply chains more freely.

This mixed result leads to the second main contribution of this paper: establishing that modularity is not a monolithic concept. Most of the modularity literature has treated it as one. For example, Schilling and Steensma (2001: 1149) followed much of the literature when they described modularity as a situation where 'a tightly integrated hierarchy is supplanted by "loosely coupled" networks of organizational actors. The loosely coupled organizational forms allow organizational components to be flexibly recombined into a variety of configurations.' This study shows that loosely coupled, reconfigurable networks and moving out of hierarchy are separate phenomena and that one can exist without the other. Future studies will need to define 'modular organizations' carefully according to their context. Greater attention to the multiple facets of organizational modularity should allow clearer, richer insights.

The third contribution is closely related. This paper shows that increasing product modularity enhances reconfigurability of organizations more quickly than it allows firms to move activities out of hierarchy.⁷ This has important managerial implications. A firm must be clear what advantages it is seeking when it begins to invest in increasing the modularity of its products. It may wish to generate a more flexible supply chain and broaden the range of suppliers with which it works. Or, it may want to increase its outsourcing, perhaps becoming a 'virtual company' (Chesbrough and Teece, 1996). A more radical shift of product design towards modularity will be required to achieve the latter than the former.

Ideally, I would be able to identify the specific forces that retard firms from moving activities out of hierarchy. Unfortunately, my data do not allow me to do so. However, looking at several possible explanations suggests important implications for

the knowledge-based view of the firm and transaction cost economics.

Both the knowledge-based view of the firm and transaction cost economics initially focused on the contrast between interactions within and between firms. However, a considerable literature (Ahuja, 2000; Dyer, 1997, 1998; Gulati, 1995; Ring and Van de Ven, 1992) has subsequently drawn on these literatures to understand changes, primarily positive, that occur in communication and governance as firms interact over time. These streams of literature have rarely intersected, leaving it unclear to what degree long-term inter-firm relationships can replace hierarchy (Hoetker, 2005, explicitly examines this question).

This paper suggests both the importance of this question and a preliminary answer. The greater modularity of computers that incorporated resolution displays reduced the importance of communications and governance advantages to the degree that long- and short-term suppliers were essentially identical from the manufacturer's viewpoint. In contrast, internal suppliers remained significantly more attractive than external suppliers. This suggests that the advantages offered by internal suppliers were significantly larger than those offered by long-term suppliers. This is consistent with both the knowledge-based view of the firm and transaction cost economics and suggests significant limits to the strategy of replacing internal production with long-term suppliers. Further theoretical and empirical work on this question would be very valuable.

An alternative explanation comes from an emergent strand of the modularity literature that focuses on the costs of developing and maintaining a modular system. Brusoni and Principe use case studies of the aeronautical engine and chemical industries to emphasize the importance of system integrators, firms that 'act as knowledge and organizational coordinators to guarantee the overall consistency of the product and to orchestrate the network of companies involved' (Brusoni and Principe, 2001: 185). For modularity to be beneficial, system integrators must divide the design and manufacturing process into appropriate modular sub-tasks and design the interfaces between components.

This process requires firms to maintain knowledge across a wide range of technological fields and activities, e.g., system design (O'Sullivan, 2001). Even under modularity, the firm may be

⁷ This is a cautious interpretation of my results. Although I actually found *no* evidence to support a relationship between product modularity and outsourcing, my results do not show that this relationship does not exist. It may or may not, but my results show that, if it does exist, it is weaker than the relationship between modularity and reconfigurability.

required to acquire and maintain knowledge about the various components in order to manage external suppliers effectively. Not only does doing so help prevent a firm from becoming dependent on a supplier, it helps a firm maintain its understanding of the system as a whole. In a study of Japanese automakers, Takeishi (2002) found that for state-of-the-art technology, automakers with greater knowledge about a component could evaluate and integrate it more effectively than firms with little component knowledge, even under a modular 'black-box' design process. Moreover, shifting production of components to external suppliers lead to the automaker losing knowledge about both individual components and the overall system. Some aspects of system-level knowledge appear to be intertwined with knowledge of the system's components.

This implies that the cost savings from moving an activity out of hierarchy are less than anticipated. The cost of retaining knowledge of the system and its various components, e.g., Toyota's investments in automotive electronics despite a sourcing relationship with Denso (Lincoln, Ahmadjian, and Mason, 1998), may blunt firms' inclination to outsource in response to changes in product modularity. Switching between suppliers is more likely to occur with modularity because it does not incur these costs.

Lastly, forces within the firm may make firms less likely to begin outsourcing in response to product modularity. Any change in organization must overcome inertia. Since inertia is greater for activities near the core of a firm's activities, switching between external suppliers requires overcoming less inertia than beginning to outsource (Hannan and Freeman, 1989). Particularly in firms that already had the ability to produce displays, this may have precluded the firm from using external suppliers, even if doing so would otherwise be optimal.

Successful product design requires overcoming challenges of communication and governance. Firms' responses to these challenges include hierarchy (internal supply) and building durable ties with rarely reconfigured sets of suppliers. This paper has shown that product modularity affects firms' use of these mechanisms differentially, advancing our understanding of the relationship between product modularity and organizational modularity. However, it has not directly explored modularity's impact on the underlying challenges

of communication and governance. Future research on these underlying challenges would help evaluate the above potential explanations for this paper's findings and perhaps suggest others. It would also contribute to both the knowledge-based view of the firm and transaction cost economics by clarifying how the mechanisms for knowledge transfer and governance differ within and between companies.

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APPENDIX: MRQAP AS A CONTROL FOR POTENTIAL NON-INDEPENDENCE OF OBSERVATIONS

Because I observe multiple decisions involving the same dyads of buyers and potential suppliers, observations may not be independent. If this is the case, coefficient estimates will be consistent, but the standard errors may be inflated. To control for this potential non-independence, I modify a technique used in social network analysis: the multiple regression quadratic assignment procedure (MRQAP) (Krackhardt, 1988). Gulati (1995) applied this method, essentially a specialized bootstrapping technique, for a similar reason.

In its standard application, MRQAP proceeds by first performing a standard multiple regression and retaining the estimated coefficients. It then randomly permutes the rows and columns of the dependent variable matrix in such a way that maintains dependencies along rows and columns, but removes their association with the independent variables. Multiple regression is performed and the

coefficients retained. This process is repeated many times.

For each coefficient, the proportion of random permutations that yielded a coefficient as extreme as the one estimated from the original data is computed. Analogous to a *p*-value in normal regression, this represents the probability of such an extreme value occurring by chance, *conditional* on the relationships in the data.

I modified this algorithm in two ways. First, I estimated a discrete choice model at each stage, rather than OLS. Second, since I did not have a square matrix of relations, I used an alternative permutation scheme.⁸ At each iteration, I permuted the values of the dependent variable for the suppliers according to a random pattern of permutations. This same pattern was used for every decision observed. This procedure preserved dependencies resulting from a supplier's identity.

Based on 1000 permutations, the QAP-estimated *pseudo-p*-values are generally greater than the originally estimated *p*-values, suggesting that non-independence of observations may have had some effect. However, all non-control variables which were previously significant at the 0.10 level continued to be so under QAP estimation.

⁸ Discussions with William Simpson at the Harvard Business School were very helpful on this point. Any error in application is, of course, mine.