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Technological Development and the Boundaries of the Firm: A Knowledge-Based Examination in Semiconductor Manufacturing

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This paper examines how the knowledge-based view (KBV) can be applied to firm boundary decisions and the performance implications of those decisions. At the center of the paper is a theoretical and empirical examination of how firms most efficiently organize to solve different types of problems related to technological development, using the semiconductor industry as the empirical setting. Measures that capture important dimensions of performance support the proposition that organization affects performance in problem solving related to knowledge development. Integrated firms realize performance advantages when problem solving in technological development is ill structured and complex, while the same is true for specialized firms when problem solving in technological development is well structured and simple. Performance differences also arise from the presence of scale economies and scope economies.

Key words: knowledge-based view; problem solving; firm boundaries; organizational boundaries
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1. Introduction

Early research within the knowledge-based view (KBV) of the firm emphasizes the importance of knowledge to create and sustain competitive advantage (Barney 1991, Wernerfelt 1984). More recent research examines how the choice of organization—in particular, the advantages of hierarchy—influences knowledge exchange and protection (Conner and Prahalad 1996; Grant 1996; Kogut and Zander 1992, 1996; Monteverde 1995). Underexplored in this literature is a theoretical and empirical examination of organizational alignment that considers the advantages and disadvantages of markets and hierarchies in knowledge development and transfer. This paper seeks to address this shortcoming by examining how firms efficiently organize to develop and transfer knowledge related to technological development.

Following previous research (Nickerson and Zenger 2004), the paper assumes that firms' primary objectives are to create valuable knowledge. However, because new knowledge often does not exist, firms must instead select particular problems to solve such that, if done successfully, yield valuable knowledge. This problem-solving approach to knowledge development is particularly germane in R&D-intensive environments, given their inherent uncertainties and complexities (Fleming and Sorenson 2004). Once a problem or set of problems is selected, firms engage in a process of search for solutions over different fitness landscapes (Gavetti and Levinthal 2000, Levinthal 1997) with corresponding interaction structures or architectures (Ethiraj and Levinthal 2004). Depending on the characteristics of problems and the magnitude and understanding of knowledge-set interdependencies within fitness landscapes, particular modes of organization are found to be advantaged in problem solving relative to other modes.

The paper undertakes a comparative empirical examination of problem-solving performance in technological development, using semiconductor manufacturing as the empirical setting. Technological development is a primary arena of competition in many R&D-intensive industries (Brown and Eisenhardt 1995). The speed and effectiveness with which new products and processes can be developed and introduced are important factors for competitive advantage. Perhaps in no other industry is this more apparent than in semiconductors, where the combination of a more competitive and global marketplace, rapid technological advancement, and increasingly sophisticated customers has resulted in steep price declines and short product life cycles. The recent industry trend toward vertical disintegration, evidenced in the organizational separation of product design and process manufacturing and the appearance of specialized firms competing directly against integrated firms (Macher and Mowery 2004), provides an ideal setting to examine comparatively the performance of alternative organizational modes in developing and transferring knowledge important to technological development. The empirical analysis compares specialized semiconductor manufacturers (e.g., the "market") and those integrated in product design (e.g., "hierarchies") using two measures of problem-solving performance in technological development. The first measure is the time from the start of process development to achievement of the first yielding product, which captures efficiencies in solving problems. The second measure is the quality of the manufacturing process, which captures the quality of solutions. The influence on performance of such factors as the structure and complexity of problems are highlighted in the empirical analysis.

The paper finds that the speed and quality of problem solving is determined in part by organizational modes that facilitate (and hinder) solution search, depending on the magnitude and understanding of the knowledge-set interdependencies within the technological landscape. Integrated manufacturers achieve performance advantages for problems that are complex and ill structured (with correspondingly complex and poorly understood interaction structures), whereas specialized manufacturers realize performance advantages for problems that are simple and well structured (with correspondingly simple and well understood interaction structures). Differences in problem-solving performance also arise from economies of scale and scope. Specialized manufacturers benefit from scope economies in technological development problem solving, while integrated manufacturers improve problem-solving performance through scale economies. Some evidence is also found that manufacturers trade off one dimension of technological development performance with the other.

The next section sets the theoretical context and presents comparative hypotheses that examine the performance effects of problem characteristics related to technological development and according to organization mode. Section 3 sets the empirical setting, highlighting in particular the importance of technological development and the trend toward vertical disintegration in the semiconductor industry. This section also describes the data sources, and the dependent and independent variables. Section 4 presents and discusses the empirical analysis and results. The final section makes concluding comments.

2. Theory and Hypotheses Development

Within the knowledge-based view (KBV), firms develop new knowledge important to competitive advantage from unique combinations of existing knowledge (Fleming 2001, Nelson and Winter 1982). Because industry dynamics can limit the sustainability of competitive advantage, firms often compete by developing new knowledge more quickly than their competitors. The KBV has predominantly underscored the virtues of hierarchy in facilitating knowledge exchange and protection. Hierarchy is argued to be beneficial on the one hand because it avoids knowledge transfer by exercising authority and directing the actions of others (Conner and Prahalad 1996, Demsetz 1988), and on the other hand because it facilitates knowledge transfer through established communication codes, shared languages, and routines (Grant 1996; Kogut and Zander 1992, 1996; Monteverde 1995). Both KBV perspectives generally ignore knowledge development and the role of markets, however. Nevertheless, an approach that discriminately compares knowledge development and transfer across organizational modes is required in order to realize a comprehensive knowledge-based theory of the firm (Nickerson and Zenger 2004).

Firms' objectives related to knowledge development and transfer influence how they organize. Because knowledge development often entails the creation of "new" knowledge that does not exist, firms must choose particular problems to solve whose solutions represent potentially valuable knowledge. Drawing on Simon's (1962) analysis of complex adaptive systems and Kauffman's (1993) NK modeling approach, previous research suggests that finding solutions to valuable problems is a process of recombinant search (Fleming 2001) over different fitness landscapes (Fleming and Sorenson 2004, Gavetti and Levinthal 2000) and complexity architectures (Ethiraj and Levinthal 2004). Fitness landscapes represent all possible combinations of relevant knowledge, with the topography of the landscape defining the value of solutions associated with particular combinations. Complexity architectures or structures represent the interdependencies between relevant knowledge sets within the landscape. Based on the number of distinct knowledge sets and the interdependence (or coupling) among these knowledge sets, some landscapes are "rugged" and discontinuous but with several high-value solutions, whereas other landscapes are smooth and continuous with single, high-value solutions (Levinthal 1997). The magnitude of the interdependencies, as well as the level of understanding of these interdependencies, influences firms' performance in realizing high-value solutions.

After identifying problems to solve, firms engage in a process of search for high-value solutions. Because solution search is often difficult, given the magnitude and level of understanding of the knowledge-set interdependencies, finding high-value solutions depends critically on how search is directed and organized (Simon 1962). Firms determine in a discriminating way how best to organize solution search that considers, simultaneously, efficiency concerns and appropriation hazards. On the one hand, economic actors require high-powered incentives that reward and support knowledge development. On the other hand, knowledge transfer between economic actors must be robust to knowledge appropriation and accumulation concerns. Problems with many knowledge sets and extensive interdependencies are more efficiently solved via search guided by heuristics, or cognitive representations of the landscape and interdependencies, and extensive evaluations of the probable consequences of search decisions. By contrast, problems with fewer knowledge sets and simpler interdependencies are more efficiently solved via directional search guided by feedback and experiential learning, whereby actors can independently pursue different approaches, observe performance, and make adjustments (Gavetti and Levinthal 2000).

This paper builds on Nickerson and Zenger (2004), who propose a knowledge-based theory of the firm based on the problem-solving and solution-search efficiencies of alternative organizational modes for knowledge generation. These authors theoretically propose a discriminating alignment between problem complexity (i.e., the degree of interdependence among knowledge sets) and alternative organizational arrangements (markets, authority-based hierarchy, and consensus-based hierarchy) that vary according to their abilities to mitigate knowledge formation hazards. The paper extends Nickerson and Zenger (2004) in two ways: First, it provides a more fine-grained examination of problem characteristics than just complexity; and second, it empirically and comparatively examines the performance implications of problem characteristics and alternative organizational modes in technological development.

Problem complexity and problem structure determine the magnitude and understanding of knowledge-set interdependencies within fitness landscapes, respectively, and suggest particular organizational approaches to solution search. Well-structured problems have formalized processes in place for solving, while simple problems do not depend significantly on interactions among knowledge sets and design choices (e.g., they are decomposable). Directional search via market modes of organization provide certain efficiencies in comparison to hierarchies, due to their more specialized expertise (Hammond and Miller 1985), high-powered incentives, and decentralized decision making (Williamson 1991). Ill-structured problems have more limited formalized problem-solving approaches in place, while complex problems are defined by substantial interdependencies among knowledge sets and design choices (e.g., they are non-decomposable). Both problem characteristics benefit from the heuristic search properties of hierarchies, as their common languages, information channels, and incentive and dispute resolution mechanisms encourage knowledge sharing, facilitate information exchange, and promote coordination in ways that market modes cannot.

In many R&D-intensive industries, technological development is a process characterized by inherent complexity, unstructured approaches, and an inability to predict success or performance ex ante. Because technological development entails the creation of new knowledge, firms select high-value problems to solve that range from ill structured to well structured, and simple to complex. Problem solving is often a trial-and-error exercise in which particular parameters are altered, learned about, and improved upon. More novel technological development is especially difficult due to the unexpected and unknown interactions between and among knowledge sets. Firms who push the technological frontier through more novel development are rewarded with first-mover advantages, but face additional costs due to the lack of a priori understanding. For instance, firms in some R&D-intensive environments simultaneously alter product and process parameters in order to achieve development success (Pisano 1997). Product innovations require entirely new manufacturing processes that are difficult or costly to implement. At the same time, process innovations that result in desired cost reductions or quality improvements also necessitate substantial product-design changes. The tasks of learning new product-design parameters are thus compounded by the need to learn, codify, and change new process-design parameters, and vice versa. The structure and complexity of problems in technological development therefore require organizational modes that can efficiently develop and transfer new knowledge across knowledge sets, production stages, and economic actors.

2.1. Problem Structure

Problems can be characterized along a continuum from ill structured to well structured. The degree of definiteness depends on the characteristics of the problem domain on the one hand and the availability and understanding of problem-solving mechanisms on the other (Fernandes and Simon 1999, Simon 1973). Well-structured problems are those with well-defined initial states and known elements, explicit approaches for solving, and accepted end states or solutions (Jonassen 2004). An example of a well-structured problem is team-sports scheduling, such that each team plays all others a certain number of times. The initial and final states are known, and there are accepted procedures for solving (i.e., use linear programming). By contrast, ill-structured problems have either poorly defined initial states or indefinite problem-solving approaches. These types of problems might also be interdisciplinary in domain or context. An example of an ill-structured problem is cycle-riding instruction, given the extensive interdependencies among the mechanics of balance, braking, pedaling, shifting, turning, etc.

The defining difference between ill-structured problems and well-structured problems is that no consensus approach exists for solving (Fernandes and Simon 1999), due to the level of understanding of knowledge-set interdependencies. Differences in understanding of the interaction structures determine the extent to which these problem types are decomposable (Ethiraj and Levinthal 2004). Ill-structured problems cannot be subdivided because of the unexpected and sometimes unknown interactions between and among knowledge sets (Levinthal 1997). A lack of understanding as to whether and how knowledge sets relate to each other makes solution search difficult. The interdependencies among knowledge sets for well-structured problems, by contrast, are better understood, making solution search more transparent. As Simon (1973, p. 186) notes, "it is not exaggerating much to say that there are no well-structured problems, only ill-structured problems that have been formalized for problem solvers." For problem solving in technological development, the major distinction between ill-structured problems and well-structured problems relates to the degree to which understanding of knowledge-set interdependencies within the technological landscape exists and formalized processes can be utilized to realize high-value solutions (Simon 1973).

This distinction between ill-structured problems and well-structured problems suggests that certain solution-search strategies realize performance benefits. Because ill-structured problems are neither predictable nor convergent in approach, they benefit from ex ante cognitive evaluations of the probable consequences of particular solution-search decisions, as opposed to ex post reliance on feedback from decisions already made (Simon 1991). Established heuristics are necessary to guide and shape ill-structured solution search because limited information exists as to whether different knowledge sets are (or are not) part of the solution space. Heuristic search strategies provide efficiency gains for these types of problems via more thorough evaluations of the probable consequences of search decisions made. By contrast, well-structured problems are effectively represented within a technological landscape such that all relevant knowledge sets are included and the path to high-value solutions is clear. The solution-search strategies for well-structured problems are also known, and sufficient information is available for solving these types of problems with only practical amounts of independent search (Simon 1973). For these better-understood knowledge-set interdependencies, directional search guided by feedback or experiential learning provides efficiency gains in achieving high-value solutions in comparison to heuristic search.

Markets realize performance advantages in finding solutions to well-structured problems due to their superior abilities to facilitate directional search. These organizational modes offer high-powered incentives, decentralized control, and mechanisms that allow individual actors to exploit and enhance their own specialized knowledge. Price acts as a high-powered incentive that motivates actors to develop this specialized knowledge (Hayek 1945). Markets face more acute competitive pressures that reduce organizational slack and increase incentives to operate efficiently (D'Aveni and Ravenscraft 1994), and are more responsive to technical and environmental change (Williamson 1985). Because the knowledge-set interdependencies are known for well-structured problems, actors can operate independently in search of high-value solutions. Hierarchies are comparatively disadvantaged for these problem types. Although hierarchies facilitate knowledge sharing and transfer, well-structured problems neither require nor benefit from these features. Moreover, the low-powered incentives, more generic knowledge sets, and bureaucratic features of hierarchies slow the speed and efficiency with which potential solutions are examined.

While market modes of organization better navigate technological landscapes for well-structured problems, they face greater challenges for ill-structured problems. Problem-solving approaches for ill-structured problems have not been formalized, and significant coordination is necessary to facilitate understanding and prioritize solution search. Markets are inefficient due to their weak support for knowledge sharing and limited protection against knowledge appropriation (Nickerson and Zenger 2004). Organizations that facilitate knowledge sharing, where information can be freely shared without risk of appropriation or accumulation and where disputes between economic actors can be monitored and resolved in a timely matter, are required instead (Teece 1992). Hierarchies are comparatively advantaged, as their firm-specific languages, communication codes, and information channels, combined with their low-powered incentives and dispute resolution mechanisms, encourage knowledge sharing and promote coordination (Grant 1996; Kogut and Zander 1992, 1996; Monteverde 1995). The formation of research and development goals and the definition of research agendas are also easier under hierarchies (Armour and Teece 1980), which are recurrent activities for ill-structured problem solving.

Thus, there are comparative performance implications for ill-structured and well-structured problems in technological development according to organizational mode. Hierarchies slow solution search for well-structured problems by adding bureaucratic costs that markets more easily avoid. At the same time, authority- and consensus-based hierarchical approaches toward dispute resolution and knowledge transfer facilitate ill-structured problem solving. While both market modes of organization and hierarchies should face greater solution-search challenges for ill-structured problems in technological development, hierarchies are better able to coordinate development tasks and promote information exchange important to understanding. The following set of hypotheses is examined:

Hypothesis 1a. *Technological development that involves ill-structured problems hinder solution search for both markets and hierarchies.*

Hypothesis 1b. *Hierarchies improve solution search for ill-structured problems in technological development, while markets hinder solution search for these problems.*

2.2. Problem Complexity

Problems can also be characterized according to their complexity, defined as the number of issues, functions, or variables involved and the degree of relationship among these properties. Complex problems have high intransparency (i.e., only some variables lend themselves to direct observation or the large number of variables requires selection of the relevant few) and significant connectivity between variables (Funke 1991). Simple problems are composed of fewer knowledge sets that interact in more predictable ways. Complex problems require the balancing of multiple knowledge sets during problem structuring and solution search, which places significant cognitive burdens on problem solvers (Jonassen 2004). Simple and complex problems also differ according to their decomposability, or degree of knowledge-set interaction. Simple (e.g., decomposable or low-interaction) problems have solutions that depend little on the interaction of knowledge sets and can readily be subdivided into subproblems that draw on these different knowledge sets, while complex (e.g., nondecomposable or high-interaction) problems entail extensive knowledge-set interaction (Nickerson and Zenger 2004).

Problem complexity and problem structure overlap, but are not identical. Ill-structured problems tend to be more complex, whereas well-structured problems tend to be less complex, but this is not a hard and fast rule. Team sports scheduling—identified above as a well-structured problem—is more complex as the number of teams or scheduling constraints increases. Cycle-riding instruction—identified above as an ill-structured problem—is less complex as the number of wheels increases (e.g., unicycle to bicycle to tricycle). Problem structure represents the level of understanding of the existing interaction structure among knowledge sets, while problem complexity captures the magnitude of these interdependencies. Technological development problems are simple if they can be solved independently from other knowledge sets, production stages, or firms. Technological development problems are complex if they rely on other knowledge sets, production stages, or firms (Langlois 1992) or require significant coordination between economic actors (Teece 1996) in order to realize high-value solutions.

Similar to problem structure, the degree of definiteness related to problem complexity suggests particular solution-search strategies. Complex problems have rugged landscapes due to the magnitude of interdependencies among knowledge sets. These problems require greater cognitive evaluations of the probable consequences of particular decisions. Established heuristics are necessary to guide problem solution search. By contrast, simple problems have more limited interactions among knowledge sets, which produce correspondingly smooth fitness landscapes. Directional search provides certain advantages to these decomposable problems via experiential learning and feedback.

Because simple problems are more easily subdivided, high-value solutions are more efficiently realized through organizational structures that operate under market-based incentives. The high-powered incentives of markets motivate actors to engage in local search to develop specialized knowledge. While markets provide weak support for knowledge sharing, this activity is largely unnecessary for simple problems, due to their decomposability (Nickerson and Zenger 2004). Hierarchies are comparatively disadvantaged for simple problems because of their low-powered incentives and added bureaucracy. Low-powered incentives constrain the incentives to develop specialized knowledge, whereas the bureaucratic costs of supporting high levels of knowledge transfer become excessive.

However, market modes of organization realize performance disadvantages relative to hierarchies for complex problems due to the extensive knowledge sharing and heuristic search required. The limited administrative controls and communication channels of markets impair the adaptive, sequential, and interrelated changes that are often necessary in complex problem solving. Instead, institutions with low-powered incentives that allow information to be shared without risk of appropriation or accumulation are required. Hierarchies are advantaged for complex problem solving in comparison because they better facilitate the dissemination of new knowledge through the formation of firm-specific languages and communication codes (Demsetz 1988, Kogut and Zander 1996, Monteverde 1995). Hierarchies are also able to more quickly alter search strategies as events unfold or new information is revealed (Masten 1984, Williamson 1985)—a likely scenario with complex problems. Globerman (1980) notes that greater complexity in the R&D demands of Canadian telecommunications firms necessitates integration with their equipment suppliers. Masten (1984) similarly argues that greater aerospace component design complexity benefits from integration because of coordination difficulties between successive production stages. While both markets and hierarchies face greater solution-search challenges with complex problems, hierarchies are better able to manage the extensive knowledge sets' interdependencies through superior administrative control and information exchange via authority or consensus building. The search for high-value solutions to complex problems is thus expected to be faster and of higher quality in hierarchies than in markets. The following set of hypotheses is examined:

Hypothesis 2a. *Technological development that involves complex problems hinders solution search for both markets and hierarchies.*

Hypothesis 2b. *Hierarchies improve solution search for complex problems in technological development, while markets hinder solution search for these problems.*

2.3. Problem Solving and Scale and Scope Economies

Size is asserted to confer performance advantages to firms through scale or scope economies (Scherer 1980). Size may also provide advantages in the conduct of firms' R&D efforts or innovative activities (Cohen 1995). Large firms may be better able to spread the fixed costs of R&D over a larger sales base in the absence of fully functioning markets for innovation (Cohen and Klepper 1996). Large firms may also be able to exploit economies of scale in the conduct of the R&D activity itself (Panzar and Willig 1981). Finally, large firms have greater access to the complementary technologies and downstream capabilities (i.e., marketing, finance, etc.) that make R&D more productive (Cohen 1995).

Despite these persuasive arguments, theoretical counterarguments have been made for each of the above propositions (Scherer and Ross 1990). Moreover, empirical findings regarding the influence of scale economies on innovative performance are mixed (Cohen and Levin 1989, Patel and Pavitt 1995). Some researchers note that these inconsistent findings result from difficulties in developing good measures of innovation (Cohen 1995), whereas others argue that a lack of sufficiently detailed data make it difficult to distinguish between economies of scale and scope (Henderson and Cockburn 1996). Direct empirical tests of whether size confers any advantages in innovative performance have also proven challenging due to the measurement difficulties associated with R&D. Some studies test whether R&D inputs (e.g., expenditures) increase more than proportionately with firm size (Cohen 1995), but this speaks only to the amount of R&D that firms invest in and says little about innovative performance. Other studies examine the relationship between firm size and R&D output measures, such as patent and innovation counts, but the results are mixed. Some find patents or innovations per R&D dollar decline with firm size (Acs and Audretsch 1988, Bound et al. 1984), while others find larger firms account for a disproportionately larger share of innovations relative to their size (Acs and Audretsch 1988, Pavitt 1987).

Scale economies likely affect problem solving in technological development for several reasons. Because technological development entails significant experimentation and trial and error, large firms are able to conduct more experiments in more diverse technological areas that facilitate knowledge development and guide problem solving in ways that small firms cannot. Firm size also allows for the development of more and different solution-search approaches. Important inputs can be spread over a larger base of development activity, which allows for greater variation in solution-search approach and increases the likelihood of obtaining high-value solutions. If firms are able to experiment with different problem-solving approaches, they can select the most efficient based on the particular characteristics of the current technological development problem. Firm size thus has performance implications for problem solving in technological development. Research suggests that beyond a certain point escalating coordination and agency costs eventually lead to diseconomies of scale (Henderson and Cockburn 1996, Zenger 1994), which are likely in problem solution search. The following hypothesis is therefore examined:

Hypothesis 3. *Scale economies improve problem-solution search in technological development, but beyond a certain point escalating coordination and agency costs lead to diseconomies of scale.*

Economies of scope are present if cost savings or performance benefits are realized when two or more activities are conducted jointly in comparison to when those activities are conducted separately (Panzar and Willig 1981). In the standard analysis of production, scope economies result when activities share productive inputs at little additional cost. Henderson and

Cockburn (1996) identify internal spillovers of knowledge as a second source of returns that results from greater diversity in R&D. Knowledge developed and accumulated in one R&D activity can be transferred to other R&D activities at little cost, but with significant performance benefits.

Scope economies in problem solving for technological development likely arise from the knowledge spillovers that Henderson and Cockburn (1996) illuminate. Knowledge developed in a given technological area is both informative and useful for future and related technological development areas. The search strategies from earlier problem-solving efforts, moreover, represent a valuable source of knowledge spillovers. Problem-solving approaches that have been developed in other technological areas can be utilized to improve the search strategies of subsequent technological development efforts. Greater scope therefore likely increases the problem-solving capabilities of organizations via improved directional and/or heuristic search. Similar to scale economies, there are likely organizational limits to scope as the costs associated with maintaining diverse problem-solving approaches in several technological areas eventually overwhelm the benefits (Henderson and Cockburn 1996, Zenger 1994). The following hypothesis is therefore examined:

Hypothesis 4. *Scope economies improve problem-solution search in technological development, but beyond a certain point, escalating coordination and agency costs lead to diseconomies of scope.*

Although the benefits of scale and scope in problem solving for technological development are clear, it is arguable whether market modes of organization possess any advantages from these economies in comparison to hierarchies (and vice versa). On the one hand, if scale economies exist it is less likely that technological development would be conducted internally, ceteris paribus. Integrated firms might instead opt for specialized firms, who are better suited to organize for and reap the benefits of these economies. By aggregating disparate demands, market modes can potentially realize superior performance from scale economies in problem solving in comparison to hierarchies because of the transactional problems associated with potential suppliers also competing as downstream rivals (Williamson 1985). On the other hand, idiosyncratic investments are often required when undertaking technological development. These specialized investments instead suggest that hierarchies should realize superior performance from problem-solving scale economies, as specialized firms have greater needs to maintain flexibility.

Market modes of organization might be in better positions to realize superior performance from problem-solving scope economies in comparison to hierarchies, because their business models are set up to aggregate the demands of several customers. Meeting a variety of customer needs requires understanding of diverse technological and functional areas that build problem-solving capabilities. Market modes are also more likely to make generic investments in comparison to hierarchies to maintain flexibility, which potentially allows for a greater number of problems to be examined. Some of the transactional issues associated with downstream competitive rivalry can also be avoided by market modes of organization in comparison to hierarchies (Williamson 1985). On the other hand, hierarchies might be better able to leverage knowledge that exists in particular in-house technological or functional activities via heuristic search, suggesting that they achieve superior performance from problem-solving scope economies. In addition, there are no a priori reasons against hierarchies making similar generic investments to maintain flexibility. As both sides of the arguments related to problem-solving scale and scope are plausible, we make no claim as to whether markets or hierarchies possess any comparative performance advantage (or disadvantage), and instead defer to the data in the empirical estimation.

3. Empirical Setting

3.1. Semiconductor Technological Development

The semiconductor industry is defined by rapid technological advancement, short product life cycles, and steep price declines. Semiconductor firms introduce new products quickly to capture the economic rents that accrue to those fast to market and able to meet demand, but this is demanding because new products usually require new manufacturing processes. This paper examines the problem-solving characteristics and performance implications of technological development between the value chain activities of product design and process manufacturing. Product design entails the design and "layout" of integrated circuits and makes extensive use of Electronic Design Automation (EDA) software that allow engineers to simulate the functional performance of new products before manufacturing commitment. Process manufacturing represents the construction of layers of conducting and insulating materials on "wafers" of silicon that give these products their function.

Technological development between these value chain activities presents many managerial, organizational, and technological problems. It is often unstructured and complex, and characterized by intricate process flows, unpredictable, yields, and idiosyncratic equipment performance. Manufacturing processes entail hundreds of interrelated steps grouped into process modules (distinct sets of operations) that are performed on different types of equipment. Although technological development is similar for most products and processes, and entails the elimination and/or modification of existing modules and introduction of new modules, it is neither well understood nor easily replicated across production facilities. Even identical technological development efforts within the same manufacturing facility can operate differently, limiting the formalization and standardization of product and process design rules. Because delays result in lost revenue and profit, the speed and quality with which firms solve problems and produce saleable product in commercially viable quantities are important determinants of competitive success.

Despite the interdependence between product design and process manufacturing, there has been a trend toward industry disintegration, exhibited in the organizational separation of these value chain activities and the appearance of specialized firms that compete directly with integrated firms (Macher and Mowery 2004). Fabless semiconductor firms design and market new semiconductor products, but rely on third parties for their manufacture. These latter firms are either specialized manufacturers (foundries) or integrated device manufacturers (IDMs) with excess production capacity. The emergence of a specialized manufacturing "market" has been facilitated by industry standardization around a single production technology and improvements in EDA software tools. Mainstream digital semiconductor products are now largely based on standard CMOS manufacturing processes, which has facilitated the division of labor between product designers, who are able to operate within relatively stable design rules, and process engineers, who are able to incrementally improve new process technologies (Macher et al. 1998). At the same time, improvements in EDA software tools provide advanced layout and simulation capability, improved design complexity, and increased portability.

3.2. Data

Data were collected as part of a global research project on semiconductor manufacturing.[1] Semiconductor firms were targeted for participation to achieve a representative sample of producers across product types, process technologies, and geography. Manufacturing facilities were selected in consultation with participating semiconductor firms under the criteria of possessing (1) advanced technologies, products, and manufacturing processes; and (2) sufficiently long production histories for longitudinal analysis. The fabrication facilities of U.S., European, Japanese, Korean, and Taiwanese semiconductor firms operating domestically and offshore are included in the sample. Most firms contacted agreed to participate. Responses were verified and elaborated on through field visits.

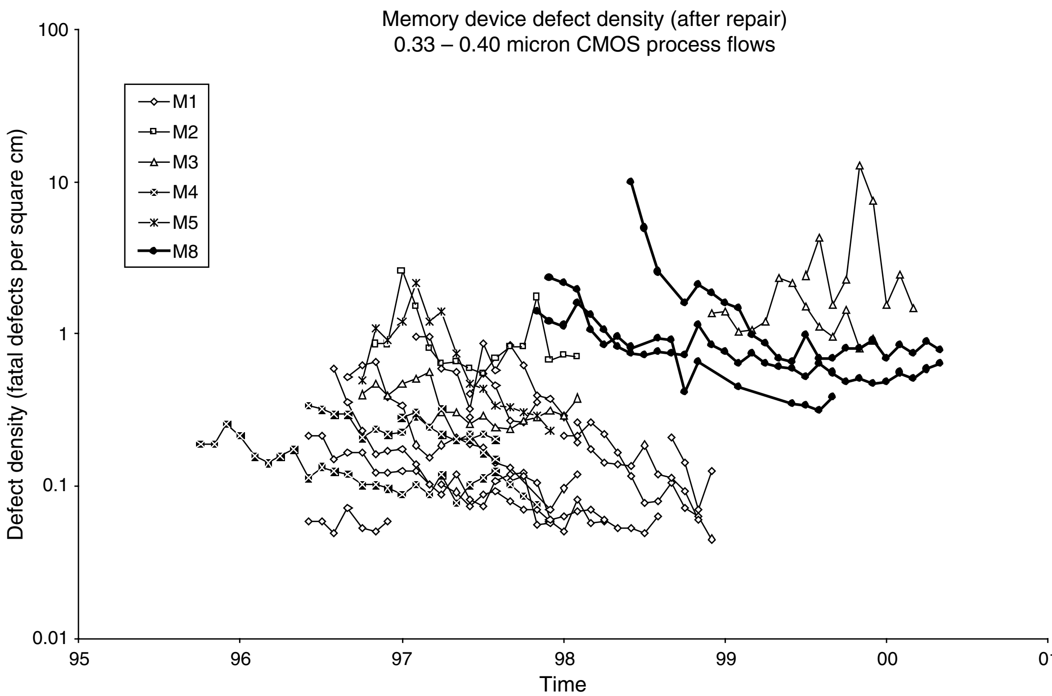
Data were collected from 36 different manufacturing facilities representing 32 different semiconductor firms from 1989 to 2001, but the empirical analysis restricts the sample from 1995 to 2001. Performance data is tailored toward manufacturing measures—yield, cycle time, equipment efficiency, etc.—but information on managerial and organizational practices utilized in the manufacturing facilities was also collected. Semiconductor firms provided historical data from the inception of a given manufacturing process, allowing for the time-series construction of performance during development, introduction, ramp-up, qualification, and full-scale operation of new processes. Although the sample represents a subset of the total number of manufacturing facilities in operation over this time period, it is representative of the industry as a whole in terms of facility size, number of process groups (e.g., distinct production lines), products manufactured, technology, etc.

3.3. Dependent Variables

Two dimensions of manufacturing performance are examined in the empirical analysis. The first measure (*Development Time*) is the time starting from the earliest stage of process development in a manufacturing facility to achievement of the first functional (or working) product, and captures efficiencies in solving technological development problems. The second measure (*Initial Yield*) is the initial yield of the semiconductor-manufacturing process, and represents the quality of technological development problem solutions. Yield in semiconductor manufacturing is expressed in terms of line yield—the proportion of wafers not scrapped—and die yield—the proportion of die on a successfully processed wafer that pass functionality tests. Common line-yield losses derive from broken or damaged wafers or skipped production process steps that render all integrated circuits (ICs) on the wafer nonfunctional, while die-yield losses are due either to random particles or to manufacturability problems. This paper compares die-yield performance, as it is considered the most important factor in wafer-processing costs and a widely accepted performance benchmark in the industry. Because die yield is sensitive to the size of the device manufactured, it is normalized into a

[1] This multiyear research project is the Competitive Semiconductor Manufacturing (CSM) Program conducted at University of California, Berkeley. The project was sponsored by the Alfred P. Sloan Foundation, with the cooperation of semiconductor producers from Asia, Europe, and the United States.

Figure 1



"density" measure of defects per square centimeter using the Murphy model:[2]

$$DieYield = \left[\frac{1 - e^{-A \cdot DD}}{A \cdot DD}\right]^2, \tag{1}$$

where A is the die area and DD is the defect density parameter. Figure 1 displays initial defect densities and rates of improvement in defect density for a subset of new processes in the sample. Superior problem-solving performance is represented in lower initial values and steeper rates of improvement. Although most semiconductor manufacturers improve over time, considerable variation in initial starting points and rates of improvement is depicted in the figure. The initial level and improvement rate succinctly describe the quality of problem solving in the manufacturing environment. Only initial defect density is examined in the empirical analysis, however, as improvement rates are based more on organizational and managerial practices that facilitate learning and problem solving within manufacturing facilities than from differences in organizational mode (Hatch and Mowery 1998, Macher and Mowery 2003).

[2] Die yield is affected by particulate contamination on the surface of the wafer, and is sensitive to the average die size on a wafer. To control for differences in average die size, yields are translated into an equivalent "defect density," or number of fatal defects per square centimeter on a wafer. See Stapper (1989) for an overview of the defect density literature.

3.4. Independent Variables

Problem Structure. Problem structure is operationalized according to semiconductor product type. Semiconductors are either analog or digital devices, with the latter further defined by their principal operations as either storage (e.g., memory) or function (e.g., logic). Differences among these product classes present different types of technological development problems, and thus require different search strategies to realize fast and high-quality solutions. The development of analog and memory products present ill-structured problems that are often described as activities based more on art than on science because of incomplete understanding of the parameter interdependencies between product design and process manufacturing. Product design changes may (or may not) require corresponding process manufacturing changes, and vice versa. These value chain activities thus play repeated games of trial-and-error and give-and-take, modifying either the product design or the manufacturing process (or both) to determine what works. Especially at the leading edge, these products have also outpaced the abilities of EDA software to adequately simulate performance prior to manufacturing commitment, compounding the structural difficulties of solving these technological development problems. A lack of codified knowledge, limited formalized processes, and an inability to predict performance ex ante limit understanding regarding the appropriate direction of search. Extensive experimentation, information exchange, and rich communication between product design and process manufacturing is instead required (Monteverde 1995). Digital logic products, by contrast, make extensive use of EDA tools that facilitate the layout and simulation of new product designs before manufacturing commitment. These latter products have also benefited from standardization around a single production technology (CMOS), which has facilitated understanding between product design and process manufacturing. Because the development of analog and memory products involves ill-structured problem solving, integrated manufacturers (e.g., hierarchies) should realize performance advantages in comparison to specialized manufacturers (e.g., markets) due to their superior heuristic search capabilities, with the opposite true for digital logic products. The variable *Problem Structure* equals one if the process manufactures analog or memory products, and is zero otherwise.

Problem Complexity. Problem complexity is measured by process linewidth, or minimum size of the smallest circuit on a device. Process linewidth is a well-accepted measure of technological sophistication (Hatch and Mowery 1998), as semiconductor technology generations have progressed along a well-defined trajectory of increasingly smaller linewidths (Langlois and Steinmueller 1999). Problems become more complex when technological development is at the leading edge due to the number and magnitude of interactions among knowledge sets. The tasks of learning the physical limits of the manufacturing process are compounded by the need to understand the functional limits of the product design and how these factors interact. New materials and/or new process steps are also typically necessary with leading-edge products. An inability to predict performance due to the magnitude of these knowledge-set interactions thus requires significant information exchange and rich communication between product design and process manufacturing to develop effective search strategies. As leading-edge linewidths vary both over time and by product type, a scaling procedure is used to adjust each sample process linewidth using industry sources that document where the leading edge was at the start of technological development. The variable *Problem Complexity* is calculated as the leading-edge process linewidth divided by the linewidth for each new manufacturing process, adjusted according to products manufactured. Process linewidths "closer" to the technological frontier present more complex problems, ceteris paribus, which should negatively impact technological development performance. This variable ranges from near zero (mature process technologies) to one (leading-edge process technologies).

Economies of Scale. Larger manufacturing facilities provide greater experimentation capacity, the examination of multiple technological options in parallel (Iansiti and West 1999), and more diverse problem-solving approaches. One important input to technological development in semiconductor manufacturing is the number of photolithography machines. As photolithography represents the "bottleneck" stage, more machines increase experimentation and problem-solving capacity. The variable *Scale* represents the number of photolithography machines in the manufacturing facility.

Economies of Scope. Semiconductor-manufacturing facilities are organized by major process groups similar to production lines. Each process group represents specific sets of procedures, operations, and equipment sets used to manufacture particular products. Economies of scope exist if the technological development activities and problem-solving approaches of one process group improve the performance of other process groups. The variable *Scope* represents the number of major process groups in the manufacturing facility.[3]

4. Empirical Analysis

Table 1 provides summary and correlation statistics for the entire sample and summary statistics disaggregated by specialized and integrated manufacturers. Of the 179 initial observations, missing data reduces the sample to 157 for the development time estimations and 171 for the yield estimations. With 32 participating manufacturing facilities over 1995–2001 included in the sample, there are roughly five process groups per facility and more than 22 observations per year. Roughly one-quarter of the data is from specialized manufacturers, who achieve shorter process development times and lower initial yields than integrated manufacturers on average.

The empirical approach utilized in the paper is similar to those found in transaction-cost economics (TCE), which suggests firms' organization decisions are based on a comparison of the performance of alternative modes of organization. Firms improve performance by aligning transactions (which differ in their attributes) with governance structures (which vary in their costs and competencies) in a discriminating and economizing way (Williamson 1991). If P_M represents the performance of markets and P_H the performance of hierarchies—where performance is broadly defined to also include cost considerations—firms choose to integrate when $P_H > P_M$ and outsource when $P_H < P_M$. Firms that do

[3] The number of products (active die) manufactured also impacts process development time in a similar fashion as the number of major process groups. This variable was tested in prior empirical specification, but the results were insignificant.

Table 1 Summary and Correlation Statistics

	Development time	*Yield*	*Technological coordination*	*Technological complexity*	*Scope*	*Scale*	*Mask layers*
Entire sample ($N = 157$)							
Mean	4.297	1.530	0.452	0.626	7.866	12.764	16.414
Standard deviation	0.851	2.450	0.499	0.186	13.108	12.879	4.382
Minimum	2.708	0.001	0.000	0.100	1.000	2.000	8.000
Maximum	6.594	20.457	1.000	1.000	55.000	49.000	30.000
Development time	1.000						
Yield	−0.346	1.000					
Technological coordination	−0.167	0.189	1.000				
Technological complexity	0.182	−0.257	0.431	1.000			
Scope	0.047	−0.079	0.111	0.199	1.000		
Scale	−0.058	−0.275	0.379	0.358	0.680	1.000	
Mask layers	−0.072	−0.164	0.602	0.470	0.105	0.377	1.000
Specialized manufacturers ($N = 42$)							
Mean	3.886	0.783	0.357	0.601	3.929	8.905	16.595
Standard deviation	0.533	0.759	0.485	0.097	1.673	1.708	2.988
Minimum	2.708	0.101	0.000	0.500	2.000	7.000	11.000
Maximum	5.199	4.918	1.000	0.857	8.000	12.000	25.000
Integrated manufacturers ($N = 114$)							
Mean	4.448	0.976	0.487	0.636	9.304	14.174	16.348
Standard deviation	0.897	1.054	0.502	0.208	15.043	14.780	4.801
Minimum	3.332	0.003	0.000	0.100	1.000	2.000	8.000
Maximum	6.594	4.527	1.000	1.000	55.000	49.000	30.000

not appropriately align transactions with governance structures are presumed to suffer performance consequences. Applying this approach to the KBV and problem-solving perspective suggests firms improve performance in knowledge-based activities by aligning problems (which differ in particular characteristics) with organizational structures (which vary in knowledge hazards, solution search, and knowledge transfer competencies) in a discriminating and economizing way (Nickerson and Zenger 2004).

Early empirical studies that simultaneously examine organization and performance utilize comparative negotiation costs (Walker and Poppo 1991) or customer satisfaction levels (Goodman et al. 1995, Mohr and Spekman 1994, Poppo and Zenger 1998), using Likert scales that are informative but potentially suffer from subjectivity and survey-participant biases (Singelton et al. 1993). Other research examines internal management costs using estimates of time spent, multiplied by a wage rate (Masten et al. 1991), but includes only internal exchanges and not external exchanges. Similar to recent research that compares the performance of organizational modes using measures that represent important dimensions of competitiveness (Leiblein et al. 2002, Nickerson and Silverman 2003, Sampson 2004), this paper examines the speed and quality with which specialized and integrated semiconductor firms solve problems in technological development. As the good being developed and transferred is predominantly knowledge based, the empirical analysis represents an ideal setting in which to add to the KBV by examining comparatively the performance implications of organizational choice in knowledge development.

Biased and inconsistent estimates obtain when examining performance between alternative organizational modes with ordinary least squares estimation, however, because firms do not choose organization randomly (Hamilton and Nickerson 2003). Organizational mode is instead chosen systematically to maximize expected performance (Heckman 1979, Madala 1983). Unobserved factors that influence both organization and performance thus create a selection bias, and normative implications drawn from these analyses are incorrect. The empirical analysis thus utilizes censored regression models that correct for misspecification in the regression equation through the addition of a selection equation (Lee 1982, Madala 1983)—in particular, one that differentiates specialized and integrated manufacturers using a vector of exogenous variables. The estimation is carried out using the Heckman procedure (Heckman 1979).

4.1. First-Stage Selection Results

Table 2 provides the first-stage selection results of the Heckman procedure. Two instrumental variables are included in the first-stage estimation that are not part of the second-stage estimation for identification (Hamilton and Nickerson 2003). The first variable (*CMOS Share*) measures the market share held by CMOS production technologies at the start of development for each new process. The growth in

Table 2 First-Stage Estimation Results

	Model 1 β (s.e.)	Model 2 β (s.e.)	Model 3 β (s.e.)
Constant	0.847 (0.536)	2.110*** (0.803)	1.801** (0.898)
Problem structure	0.425 (0.282)	0.955*** (0.354)	0.979*** (0.358)
Problem complexity	0.585 (0.743)	3.591*** (1.367)	3.697*** (1.394)
Scope	0.099* (0.060)	0.311*** (0.106)	0.406*** (0.139)
Scope^2			−0.0001 (0.0158)
Scale	0.015 (0.016)	−0.018 (0.029)	0.019 (0.098)
Scale^2			−0.008 (0.020)
Mask layers	−0.081*** (0.030)	−0.043 (0.049)	−0.044 (0.050)
CMOS share		−0.061*** (0.015)	−0.063*** (0.016)
Design productivity		−0.0003* (0.0002)	−0.0003* (0.0002)
N	171	171	171
Log *L*	−87.03	−55.27	−54.05
R^2	0.08	0.43	0.45
LR (*zero slopes*)	20.98***	84.50***	85.33***

Note. Dependent variable (Z_i) equals 0 for specialized manufacturers and 1 for integrated manufacturers.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

dominance of standard CMOS production processes has facilitated the division of labor between product designers, who can operate within relatively stable design rules, and process engineers, who are able to incrementally improve new process technologies (Macher et al. 1998). The second variable (*Design Productivity*) measures the state of design productivity for semiconductor products at the start of development for each new process.[4] This variable captures the advances made in EDA software tools that have facilitated the exchange and standardization of product design data both between and within semiconductor design and manufacturing firms (Macher et al. 2002). While these developments have facilitated the division of labor and the exchange of design information, their effects are similar between independent product design and manufacturing firms working together and between product design and manufacturing divisions within the same firm. These developments have not directly affected firm performance because no a priori advantages have resulted for either organizational mode. Because they represent industry developments over time that each mode of organization faces, they are appropriate instruments.

Model 1 presents a baseline that consists of the main independent variables of interest. Model 2 includes the instrumental variables described above. Model 3 adds the squared terms for scale and scope economies. Both Model 2 and Model 3 represent an improvement in fit over Model 1 ($\chi^2(2) = 63.52$, $p < 0.01$ and $\chi^2(4) = 65.96$, $p < 0.01$, respectively). Model 3 is not an improvement in fit over Model 2 ($\chi^2(2) = 2.44$, $p > 0.1$), but is the appropriate model for hypotheses testing. As expected, the Model 3 results indicate that hierarchies are more likely as problems in technological development are ill structured and complex ($p < 0.01$, respectively). Both results provide preliminary support for the argument that firms seek organizational modes that improve heuristic search capabilities when solving these types of problems. Model 3 also indicates that the *CMOS Share* and *Design Productivity* have the predicted and statistically significant effects on organization ($p < 0.01$ and $p < 0.10$, respectively).

4.2. Second-Stage Performance Results

Tables 3 and 4 provide the second-stage performance results using problem-solving speed (*Development Time*) and problem-solving quality (*Initial Yield*), respectively. It is recognized that these problem-solving performance measures are correlated, but there is little value in moving from ordinary least squares (OLS) to generalized least squares (GLS) estimation for two reasons: First, the correlation between development time and yield is moderate ($p = 0.35$); and second, the OLS and GLS results obtained are identical because the development time and yield equations have identical explanatory variables (Greene 1998). The estimation therefore examines the problem-solving speed (*Development Time*) separately from problem-solving quality (*Yield*).

Model 1 presents a baseline that includes the main independent variables of interest but excludes the Inverse Mill's Ratio. Model 2 adds the Inverse Mill's Ratio for comparison to Model 1. Model 3 adds the squared terms for scale and scope economies. F-tests that all of the coefficients have zero slopes are rejected in all models and in both tables. The Inverse Mill's Ratio corrects the error terms in the performance equations to achieve consistent and unbiased estimates. A comparison of the results of Model 2 to

[4] *CMOS Share* is derived from Integrated Circuit Engineering's (ICE) Status data books. Since 1964, ICE has published an annual report on the integrated circuit industry that measures market share of all IC process technologies. *Design Productivity* is derived from a study by SEMATECH that derived historical measures of the level of design automation and design productivity in the industry. These data were verified for accuracy using Integrated Circuit Engineering's (ICE) Status data books that have conducted similar studies.

Table 3 Development Time Results

	Model 1		Model 2		Model 3	
	SM β (s.e.)	IM β (s.e.)	SM β (s.e.)	IM β (s.e.)	SM β (s.e.)	IM β (s.e.)
Constant	2.840*** (0.791)	3.600*** (0.377)	2.913*** (0.831)	3.563*** (0.381)	3.055 (2.689)	3.671*** (0.433)
Problem structure	−0.048 (0.156)	−0.842*** (0.220)	−0.082 (0.160)	−0.827*** (0.219)	0.008 (0.112)	−0.718*** (0.224)
Problem complexity	2.917*** (0.897)	1.440** (0.540)	2.648*** (0.954)	1.456*** (0.541)	1.876** (0.762)	1.479*** (0.541)
Scope	−0.070 (0.065)	0.004 (0.004)	−0.066 (0.064)	0.004 (0.004)	−0.946*** (0.181)	0.023 (0.054)
Scope^2					0.095*** (0.019)	0.000 (0.001)
Scale	−0.031 (0.061)	−0.008* (0.005)	−0.025 (0.062)	−0.010* (0.005)	0.542 (0.651)	−0.055** (0.023)
Scale^2					−0.034 (0.038)	0.001** (0.000)
Mask layers	−0.008 (0.029)	0.026 (0.021)	−0.008 (0.028)	(0.029) (0.022)	−0.020 (0.021)	(0.031) (0.022)
Lambda			−0.353* (0.207)	−0.782*** (0.273)	−0.448** (0.199)	−0.827*** (0.293)
N	42	115	42	115	42	115
Log *L*	−24.52	−139.10	−23.98	−138.35	−12.39	−136.93
Adjusted R^2	0.23	0.14	0.23	0.14	0.53	0.15
LR (*zero slopes*)	3.43**	4.61***	3.00**	4.09***	6.72***	3.42***

Note. SM is specialized manufacturers and IM is integrated manufacturers.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

those in Model 1 indicates that the coefficients are broadly similar in magnitude and sign, but generally with larger standard errors. Justification for the Heckman procedure is found in Tables 2 and 3 as the Inverse Mill's Ratio coefficients are significant, which is interpreted as unobserved characteristics of one organizational mode influencing problem-solving performance in technological development relative to the other mode. There are absolute advantages for specialized manufacturers in the speed of problem solving, and comparative advantages for each type of manufacturer in the quality of solutions (Dolton and Makepeace 1987, Madala 1983). The Heckman results in Tables 3 and 4 suggest that overall the influence of organizational mode choice on technological development performance is driven in part by an endogenous selection process.

Model 3 in Tables 3 and 4 provides the basis for hypothesis testing. The coefficient estimates are used to determine whether and how problem characteristics affect solution-search performance of specialized and integrated semiconductor manufacturers, and thereby provide tests of the "A hypotheses." Some determination of how a problem characteristic influences specialized manufacturers relative to integrated manufacturers (and vice versa) in solution search is achieved by comparing the sign and magnitude of coefficients (β_{SM} and β_{IM}) and their standard errors using t-statistics (Poppo and Zenger 1998). Because the coefficient estimate comparisons only indicate the impact of a problem characteristic for one mode of organization relative to the other, Table 5 presents a performance comparison for both modes of organization, and thereby provides tests of the "B hypotheses."

The Model 3 results of Table 3 indicate that problem structure is not statistically significant for specialized manufacturers, but is positive and significant for integrated manufacturers ($p < 0.01$), which does not support Hypothesis 1a. A t-test comparison between the problem structure coefficients and their standard errors achieves statistical significance, however, and indicates that ill-structured problems have a smaller impact on problem-solving speed for integrated manufacturers relative to specialized manufacturers. This finding supports the proposition that hierarchies better facilitate the heuristic search that is necessary for ill-structured technological development problems. The Model 3 results also indicate that problem complexity has a hypothesized performance effect for both specialized ($p < 0.05$) and integrated ($p < 0.01$) manufacturers, which supports Hypothesis 2a. As semiconductor manufacturers take on complex technological development problems, performance, not

Table 4 Initial Yield Results

	Model 1		Model 2		Model 3	
	SM β (s.e.)	IM β (s.e.)	SM β (s.e.)	IM β (s.e.)	SM β (s.e.)	IM β (s.e.)
Constant	−3.206* (1.768)	1.597*** (0.243)	−4.285*** (1.584)	1.788*** (0.266)	−1.762 (21.709)	1.271*** (0.360)
Problem structure	0.280* (0.148)	0.463** (0.195)	0.492** (0.198)	0.563*** (0.201)	0.454 (0.433)	0.619*** (0.201)
Problem complexity	4.586*** (1.725)	−2.521*** (0.506)	7.860*** (1.887)	−3.492*** (0.684)	7.202** (2.976)	−2.825*** (0.779)
Scope	−0.136*** (0.049)	0.019*** (0.005)	−0.150*** (0.043)	0.031*** (0.007)	−1.181 (5.587)	0.090** (0.045)
Scope^2					−0.088 (0.190)	−0.002** (0.001)
Scale	0.149** (0.074)	−0.020*** (0.004)	0.007 (0.090)	−0.019*** (0.003)	−0.141 (0.898)	−0.029*** (0.005)
Scale^2					0.072 (0.284)	0.000*** (0.000)
Mask layers	−0.098** (0.042)	0.035** (0.018)	0.010 (0.050)	0.017 (0.019)	0.024 (0.055)	0.030 (0.020)
Lambda			1.780*** (0.427)	−0.697*** (0.270)	1.678* (0.929)	−0.573* (0.329)
N	57	114	57	114	57	114
Log *L*	−48.86	−138.60	−44.78	−138.60	−44.32	−133.72
Adjusted R^2	0.37	0.37	0.44	0.37	0.43	0.40
LR (*zero slopes*)	7.54***	14.16***	8.39***	14.16***	6.24***	10.55***

Note. SM is specialized manufacturers and IM is integrated manufacturers.
***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

surprisingly, suffers. Although this effect is smaller for integrated manufacturers in comparison to specialized manufacturers, a t-test comparison of coefficients does not achieve statistical significance. As hypothesized, scope economies have a positive effect on performance for specialized manufacturers ($p < 0.01$), providing partial support for Hypothesis 3. Specialized manufacturers that operate several distinct process groups are able to take advantage of knowledge spillovers in problem-solving approaches for technological development, but eventually face coordination challenges as the number of process groups increases. Integrated manufacturers do not benefit from problem-solving scope economies for this technological development performance measure, but instead benefit from scale economies ($p < 0.05$), which provides partial support for Hypothesis 4.

The top half of Table 5 shows the speed of problem solving for specialized and integrated manufacturers, holding all variables at their respective means and varying a particular problem characteristic of interest. Specialized manufacturers solve well-structured problems more quickly in comparison to integrated manufacturers, but no significant difference exists for ill-structured problems—results that provide partial support for Hypothesis 1b. Market modes of

Table 5 Performance Effect of Problem Type

	SM	IM	t-test
Development time			
Problem structure			
Well-structured	3.862	4.812	6.452***
"Mean" level	3.865	4.462	4.058***
Ill-structured	3.870	4.094	1.521
Problem complexity			
Minimum	3.676	3.670	−0.040
Mean − S.D.	3.682	4.154	3.202***
Mean	3.865	4.462	4.058***
Mean + S.D.	4.047	4.770	4.914***
Maximum	4.346	5.001	4.453***
Initial yield			
Problem structure			
Well-structured	0.566	0.456	−0.704
"Mean" level	0.734	0.760	0.167
Ill-structured	1.021	1.075	0.345
Problem complexity			
Minimum	Out of sample	1.760	N/A
Mean − S.D.	0.049	1.294	7.940***
Mean	0.734	0.760	0.167
Mean + S.D.	1.419	0.226	−7.606***
Maximum	2.019	Out of sample	N/A

Note. SM is specialized manufacturers and IM is integrated manufacturers.
***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

organization thus achieve faster solution search for well-structured problems in technological development. Table 5 also shows development time against a continuum (minimum, "low," "average," "high," and maximum) of increasingly complex problems for both modes of organization. No support is found for Hypothesis 2b, as specialized manufacturers are faster in solving problems, regardless of their level of complexity.

Table 4 presents the performance results with problem-solving quality (*Initial Yield*) as the dependent variable. The Model 3 results indicate that problem structure has a positive effect for specialized manufacturers and positive and significant effect for integrated manufacturers ($p < 0.01$), which provides partial support for Hypothesis 1a. A *t*-test comparison between the coefficients and their standard errors does not indicate any statistically significant difference by organizational mode, however. The problem complexity coefficients are positive and significant for specialized manufacturers ($p < 0.01$), and negative and significant for integrated manufacturers ($p < 0.01$). A *t*-test comparison does indicate a statistically significant difference on problem-solving quality by organizational mode ($p < 0.01$). Problem complexity thus creates greater challenges for specialized manufacturers in comparison to integrated manufacturers for this performance measure, due to the ineffective directional search strategies of market modes. Hierarchies are better able to utilize authority or achieve consensus in developing heuristic search strategies for solving these types of problems. The Model 3 results also indicate the presence of scope diseconomies and scale economies for integrated manufacturers, and scope economies for specialized manufacturers. Specialized manufacturers realize quality performance benefits through spillovers of different problem-solving approaches ($p < 0.05$), whereas integrated manufacturers realize quality performance improvement benefits through increases in problem-solving capacity ($p < 0.01$).

The bottom half of Table 5 depicts the performance impact of problem structure and problem complexity on initial yield performance by organizational mode. Although integrated manufacturers achieve superior performance in comparison to specialized manufacturers, there is no statistically significant performance difference for this problem characteristic, which fails to support Hypothesis 1b. Table 5 also shows initial yield performance against a continuum of increasingly complex technological development problems for both modes of organization. Strong support is found for Hypothesis 2b, as specialized manufacturers achieve higher-quality solutions for technological development that involves simple problem solving, whereas integrated manufacturers achieve higher-quality solutions for technological development that requires complex problem solving. These results support the hypothesis that the unique search strategies available to markets and hierarchies drive performance differences for simple and complex problem solving.

4.3. Discussion

The empirical results support the arguments that the structure and complexity of problems related to technological development influence both the mode of organization and subsequent performance. Ill-structured problems in technological development are more likely to be solved in hierarchies due to organizational approaches that facilitate understanding. Complex problems are also more likely to be solved in hierarchies because knowledge-set interdependencies are more easily managed from improved information exchange via authority or consensus building.

In terms of performance, specialized manufacturers solve well-structured problems faster in comparison to integrated manufacturers. Specialized manufacturers also outperform integrated manufacturers in both the speed and quality of problem solving for simple problems, while integrated manufacturers outperform specialized manufacturers in problem-solving quality for more complex problems. There are thus relative performance advantages in solving simple and complex problems that are dependent upon organizational mode for both performance measures. These findings provide empirical support to the theoretical arguments that alternative organizational arrangements facilitate particular solution-search strategies for problem solving in technological development. What drives superior performance is not organization per se, but the alignment between organization and the underlying attributes of the phenomenon examined (Leiblein et al. 2002, Sampson 2004). Hierarchies often look inefficient relative to markets, but such claims are naïve, as these organizational modes often undertake the most difficult problems (Gibbons 2005).

The problem structure estimates for development are negative for integrated manufacturers—a counterintuitive result that suggests that performance improves as technological development problems become ill structured. This finding can be explained by several factors. Technological development for memory and analog products (ill-structured problems) is more incremental in comparison to logic products (well-structured problems), and more readily builds on prior development efforts. Incremental approaches are necessary for these products to control costs and achieve workable solutions, but nevertheless still require close coordination between product design and process development. This result also highlights the time-to-market and manufacturing performance trade-off that exists in this and other industries. Firms that operate in R&D-intensive environments often face trade-offs between the market requirements for time-to-market and the constraints of cost-effective (high-quality) manufacturing. When technological development immaturity significantly increases manufacturing costs through poor quality, the benefits of being fast to market are dissipated. At the same time, an overly slow approach to technological development can shorten the relevant window of market opportunity. Semiconductor firms face challenges not only in solving technological development problems, but also in prioritizing which problems (both speed- and quality-related) to solve.

The problem complexity coefficient estimates for the quality of problem solving were positive for specialized manufacturers and negative for integrated manufacturers—results that indicate that problem complexity creates greater managerial challenges and has larger performance implications between firms than within firms. Differences in decision rights over the path of search, as well as communication channels that support knowledge transfer between these distinct organizational modes, help to explain this result. The common language and communication codes that exist between product designers and process developers in integrated settings are advantaged not only in heuristic search, but also in transferring knowledge across this interface because the economic actors are relatively unchanging. By contrast, specialized manufacturers provide manufacturing services to a consistently changing set of product designers, which makes knowledge development and transfer more difficult in comparison.

The performance measure comparisons highlight some of the differences in strategic approach and inherent trade-offs that exist in technological development for specialized and integrated manufacturers. Specialized manufacturers generally realize faster technological development times in comparison to integrated manufacturers, while the same is true for integrated manufacturers in initial quality. The results underscore the importance that specialized manufacturers place in meeting delivery deadlines, and the emphasis that integrated manufacturers place in cost-effective manufacturing. These firms thus prioritize strategic importance and make trade-offs based at least in part on that strategic focus. Both the speed and quality of technological development are nevertheless important dimensions of competitiveness—not mutually exclusive objectives.

Although specialized manufacturers offer flexibility to product design firms and integrated firms who outsource manufacturing, the empirical results suggest that these firms also come with certain risks. Specialized manufacturers provide advantages in problem-solving speed in comparison to integrated manufacturers, but disadvantages (especially at the technological frontier) in the quality of solutions. Specialized manufacturers are thus not likely to completely replace integrated manufacturers because of this performance trade-off. Semiconductor firms who outsource technological development that requires heuristic search and substantial knowledge transfer between knowledge sets and economic actors in order to solve ill-structured or complex problems may therefore be placing themselves at a competitive disadvantage in comparison to those that keep this value chain activity in-house. These results thus help to underscore the circumstances where outsourcing makes sense, and support the proposition that own-firm and supplier capabilities influence outsourcing decisions (Argyres 1996).

This paper is not without limitations. The empirical setting is somewhat unusual, characterized by rapid technological advancement, complex product design, and process manufacturing environments. While detailed data are critical for examining organization and performance in firms' knowledge development and transfer activities, the analysis takes place in a single industry. Given the uniqueness of the semiconductor industry, the generalizability of empirical results to other industries—particularly outside high-technology industries—may be limited. The evidence presented is also restricted to two dimensions of performance. Although the speed and the quality of problem solving in technological development are important aspects of competitiveness, other performance dimensions influence and shape the ways in which semiconductor firms compete and build competitive advantage.

5. Conclusion

This paper contributes to the knowledge-based view (KBV) in its examination of how knowledge development and transfer influence firms' boundary decisions and the performance implications of those decisions. At the center of the paper is an examination of how firms organize efficiently to solve different types of problems related to technological development, using the semiconductor-manufacturing industry as the empirical setting. The paper adds to the knowledge-based theory of organizational alignment for the development of knowledge-based assets by taking a theoretically and empirically comparative approach. It finds performance differences in problem solving for technological development between firms specialized in semiconductor manufacturing and those integrated in product design and semiconductor manufacturing. These differences provide empirical support to the theories that the structure and complexity of problems related to firms' technological development efforts have distinct effects on the problem-solving performance of alternative modes of organization.

Integrated manufacturers (hierarchies) achieve performance advantages when technological development involves complex problems. Hierarchies are effective in solving these types of problems because their communication structures and organizational mechanisms facilitate heuristic search through authority or consensus building. At the same time, specialized manufacturers (markets) realize performance advantages when technological development involves well-structured and simple problems. Market modes of organization improve both the speed and quality of problem solving through directional search due to their high-powered incentives and specialized expertise.

The theoretical arguments and empirical results present a number of interesting organizational and managerial implications. They first underscore the influence of organization on technological development performance in general (Chesbrough and Teece 1996). An important advantage of hierarchies in comparison to market modes of organization for technological development is the formation of organization-specific routines related to knowledge development and transfer. When technological development involves ill-structured or complex problems, hierarchies improve information dissemination, increase understanding, and align incentive structure regarding the path of search in comparison to market modes of organization. At the same time, market modes of organization offer important advantages in comparison to hierarchies when technological development involves well-structured or simple problems, due to their high-powered incentives and more direct competitive pressures.

The inherent trade-offs that exist between the high-powered incentives of markets and the superior administrative control of hierarchies implies that firms need to match the problem-solving requirements of technological development with organizational modes that improve solution search and facilitate knowledge development and transfer to maximize performance. The theoretical arguments and empirical results presented thus contest the theory that attributes of exchange impose equal damage (or benefit) on markets and hierarchies (Alchian and Demsetz 1972). Although these modes of organization share many common features, each possesses particular strengths and weaknesses relative to problem solving and solution search important for knowledge development and transfer in firms' technological development activities.

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