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# BIGGER AND SAFER: THE DIFFUSION OF COMPETITIVE ADVANTAGE

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*Research on the diffusion of technologies that give competitive advantage is needed to understand the role of technology in competition. Predictions on which firms first obtain useful technologies are made by cluster theory, which holds that the diffusion is geographically bounded, and network theory, which holds that adoption is more rapid in central network positions. These predictions can be evaluated using data on the diffusion of supplier innovations that give competitive advantage to firms in the buyer industry. Here, the diffusion of new ship types is studied using the heterogeneous diffusion model and data on shipping firm-shipbuilder networks, showing that valuable innovations remain rare because they are not adopted by distant firms in geographical and network space. The strong influence of geographically dispersed interfirm networks on technology diffusion justifies a greater role of interorganizational networks in the theory of competitive advantage.* 

## INTRODUCTION

Organizational performance and survival chances vary greatly across organizations. Some of this variation results from well-known differences in the competitiveness of industries or temporal changes in the economic cycle (Rumelt, 1991; McGahan and Porter, 1997), and does not represent an empirical puzzle. Some variation appears to be temporary and largely random, and has not interested researchers. What remains are relatively persistent intraindustry firm differences with no ready explanation except that the high-performing firms have a competitive advantage. Having identified competitive advantage through its consequences for performance is not the same as understanding it, however, because it only means that firms that appear similar based on current theory may differ in one or more characteristics with less known consequences. Thus, a search is on for the source(s) of competitive advantage. Topics such as top management teams (Carpenter, 2002) and firm scope (Li and Greenwood, 2004) have interested researchers because of their potential implications for competitive advantage.

An important proposition is that innovations are sources of competitive advantage. The resource-based view argues that resources give sustainable competitive advantage if they are difficult to transfer (Reed and DeFillippi, 1990; Barney, 1991) or require prior investment to utilize (Dierickx and Cool, 1989; Kogut and Zander, 1992). Major technological innovations fulfill these conditions because they tend to spread slowly (Gort and Klepper, 1982) and to be adopted more rapidly by firms with high technological capabilities (Dewar and Dutton, 1986). However, an important insight from research on the diffusion of innovations is that it is not just the capabilities of the firm that

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predicts early adoption of innovations, but also its centrality and social proximity to these innovations (Rogers, 1995; Strang and Soule, 1998).

Two theories of competitive advantage make predictions on how firms can become early adopters through proximity to innovations. First, cluster theory argues that competitive advantage is created in the interfaces between firms and their customers and suppliers, and thus one can find clusters of highly capable firms in close proximity to each other (Porter, 1990). Second, network theory argues that certain network positions give privileged access to knowledge and resource flows (Uzzi, 1996; Powell, Koput, and Smith-Doerr, 1996). These arguments have different implications for the diffusion of technological innovations. Cluster theory predicts selective diffusion within a spatially bounded social system, and network theory predicts selective diffusion through preexisting interfirm relations.

Work on the diffusion of innovations has produced findings that can be taken as broadly supportive of either theory of competitive advantage. Cluster theory is supported by evidence that the diffusion of innovations is more rapid over short distances (Burns and Wholey, 1993; Rao, Davis, and Ward, 2000; McKendrick, Doner, and Haggard, 2000; D'Aunno, Succi, and Alexander, 2000). Network theory is consistent with evidence that interorganizational networks facilitate innovation diffusion (Davis and Greve, 1997; Kraatz, 1998; Haunschild and Beckman, 1998; Ahuja, 2000; Tsai, 2001). Closer analysis suggests caution in applying these results to the theory of competitive advantage, however, because many innovations examined in diffusion research are not strategically important. The great rewards from obtaining competitive advantage and the significant capability to absorb external knowledge held by some firms suggest that innovations that give competitive advantage may spread rapidly even if their owners seek to isolate them (Cohen and Levinthal, 1990).

The connection between these theories of competitive advantage and research on innovation does, however, show that we can evaluate how well the diffusion of strategically important innovations fits the predictions from each theory. If strategically important innovations spread slowly and selectively within geographical clusters, then proximity to an innovator can be a source of competitive advantage. If they spread slowly and selectively through networks, then network position can be a source of competitive advantage. These theories are usually conceived as competing explanations of competitive advantage, which is true with respect to their emphasis. The arguments are complementary in principle, however, and below it will be shown how they can be tested in a single model of innovation diffusion.

Diffusion analysis is not the most common empirical strategy for testing these theories. Cluster theory has identified clusters and described their persistence and success qualitatively (e.g., Porter, 1990) or analyzed the impact of clusters on employment and economic growth (e.g., Porter, 2003). Network theory has applied a broad range of methods including diffusion studies (Brass *et al*., 2004), but network diffusion studies usually examine technologies or institutions with uncertain effects on the competitive advantage of the adopter, and thus do not address the effect of network position on competitive advantage as directly as studies linking network position to innovativeness or survival (Uzzi, 1996; Ahuja, 2000; Tsai, 2001).

Diffusion processes matter for competitive advantage because of the old tension between theories that view the value of the innovation as the primary driver of diffusion and theories that view social influence from other adopters as more important (Karshenas and Stoneman, 1993). The view that the value is more important implies accurate evaluation and hence the possibility of an efficient factor market for innovations, making them unimportant for competitive advantage unless their spread can be limited by means such as secrecy or patent protection (Barney, 1986). By contrast, the view that social influence is more important is built on the claim that decision makers let trusted sources of information such as network contacts resolve uncertainty on the value of an innovation (Coleman, Katz, and Menzel, 1966; Haunschild, 1993; Palmer, Jennings, and Zhou, 1993).

Here, the diffusion of two innovative ship designs is analyzed. Ships are investment goods with significant consequences for the costs and services of shipping companies, and are thus potential sources of competitive advantage. Though ship designs are important for shipping companies, they rely on shipbuilders to develop new ship types and customize existing ship types. Thus, competitive advantage in the form of a better ship design is created either in a shipbuilding company or in the customer-supplier interface of the shipping and shipbuilding companies. The question is where it goes from there—does it stay in the focal shipping company, does it spread locally within a cluster of shipping companies, or does it spread through network ties? This strategic situation is known from other industries in which firms rely on advanced production equipment developed by suppliers, such as robots in various manufacturing industries (Katila and Ahuja, 2002), computer-controlled tools in metalworking (Harrison, Kelley, and Gant, 1996), and transaction processing equipment in retail (Levin, Levin, and Meisel, 1987), and it presents firms with a dilemma. On the one hand, adoption of a superior technology is an opportunity to gain competitive advantage. On the other hand, the availability of the same technology to other firms means that the opportunity will only be realized if others for some reason fail to adopt it. Thus the question is, when do valuable innovations spread so slowly and selectively that they give competitive advantage to early adopters?

## COMPETITIVE ADVANTAGE THROUGH DIFFUSION

### Limited diffusion and resource advantage

The resource-based view of the firm argues that resources give sustained competitive advantage when they are valuable, rare, imperfectly imitable, and not substitutable (Barney, 1991). Resources must yield a superior product/service or lower costs in order to be valuable, and they must be rare to ensure that the resource holders do not compete away the value they create. The resources must be imperfectly imitable and not substitutable in order to prevent entry using either the same resource or an equivalent one. Of these conditions, the imperfect imitability condition is of special interest to diffusion analysis. The role of imperfect imitability in the theory is to prevent rapid diffusion of the resource, which would otherwise lead to dilution of the competitive advantage gained from it.

The conditions for when a resource is imperfectly imitable have been considered by several scholars (Lippman and Rumelt, 1982; Reed and DeFillippi, 1990; Barney, 1991; Kogut and Zander, 1992). The strong form of the argument holds that tacit knowledge must be involved in the resource or in its application in order for the resource to be imperfectly imitable (Reed and DeFillippi, 1990). The weak form of the argument maintains that for competitive advantage to endure, it may be sufficient that the resource or its application is complex and thus difficult to replicate, or that the resource can only be replicated with a time lag (Dierickx and Cool, 1989; Kogut and Zander, 1992; Rivkin, 2001). This argument has been applied to intangible resources such as reputations, trust, and routines (Dierickx and Cool, 1989; Cockburn, Henderson, and Stern, 2000), but it also applies to tangible assets that cannot be accumulated quickly. Technological innovations fulfill this criterion when they are complex in themselves or require complex adaptations of the production system.

Empirical work has examined whether the knowledge embedded in an innovation predicts how quickly it is voluntarily transferred to another organization or involuntarily imitated, finding that more easily codified and teachable innovations were transferred sooner, but were not more likely to be imitated (Zander and Kogut, 1995). This study also showed that imitation times were generally long and not appreciably shorter for innovations of low complexity. Another study examined whether different understanding or different incentives explained the failure of independent firms to imitate routines used by successful franchise organizations, finding that the understanding of effects had the greatest impact (Knott, 2003). This study also showed that many valuable routines did not spread widely even though they were well described. Such observations justify the view that some innovations spread slowly enough to give competitive advantage, and that such innovations are selectively adopted by firms that have greater capacity to absorb new knowledge (Cohen and Levinthal, 1990). Indeed, these observations suggest that an innovation does not need to involve tacit knowledge or complexity to spread slowly: uncertainty about the value is sufficient.

Uncertainty about the value is an important reason for slow and selective diffusion of innovations. The long life of production assets is a dilemma when an innovative production technology becomes available, because uncertainty about its value relative to better-known technologies makes adoption risky. The innovation can have high and long-lasting value so that it should be adopted, it can have unanticipated costs or disadvantages so that it should be avoided, or it may soon be superseded by a superior generation



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so that it is better to wait. The uncertainty causes wide variation in managerial evaluations of its value, so that the initial adoption decision becomes a function of optimism as much as of actual knowledge (Harrison and March, 1984; Barney, 1986). Once the firm has adopted an innovation, however, it will accumulate experience that allows more precise judgment of the value. It will also gain competence in its use, increasing the expected value of the focal technology relative to others (Levitt and March, 1988). Hence, if the innovative technology provides competitive advantage, the firm will acquire more of it in order to build a cumulative advantage through having a larger base of the most efficient technology than its competitors (Dierickx and Cool, 1989; Kogut and Zander, 1992). This argument makes no prediction on initial adoptions, but predicts that subsequent acquisitions are more likely as a result of the knowledge gained through the first adoption:

*Hypothesis 1: Firms that have adopted an innovation have an increased propensity to acquire it again.*

## Local diffusion and regional advantage

If uncertainty limits the spread of valuable innovations, then it is natural to consider whether some firms, but not all, learn about the value of an innovation through observation of others or direct communication. If such learning occurs, then a firm can gain competitive advantage by being positioned to learn the value of an innovation before other firms do. Geographical proximity is one mechanism that has been linked to competitive advantage in cluster theory. Although alternative explanations of firm clusters exist (e.g., Krugman, 1991), the 'diamond model' (Porter, 1990) is a representative and influential theory that posits a set of interrelated processes with effects on firm capabilities. First, intense firm rivalry will push individual firms to develop better products and production technologies in order not to fall behind their competitors. Second, high customer demands trigger such rivalry, and are in turn escalated by the experience of receiving frequent improvements in product characteristics or costs. Third, the capabilities of firms in related and supporting industries are improved because the high pace of innovation in the focal industry requires close cooperation and exchange of ideas with industries providing inputs or supporting services. Finally, factors of production such as employees benefit from the upgrade of firm capabilities triggered by rivalry.

An important part of the empirical work to verify this theory has been studies documenting firm clusters at the national or regional level (Porter, 2000; 2003) and local spread of knowledge (Jaffe, Trajtenberg, and Henderson, 1993; Pouder and St. John, 1996; Audretsch and Feldman, 1996). Detailed studies of transactions also support the claim that supplier-buyer ties among nearby firms are important (Lazerson, 1995; Uzzi, 1996). Particularly strong support has been gathered from studies showing local spillover of valuable knowledge in emerging industries with rapid technological progress such as semiconductors (Saxenian, 1994) and biotechnology (Powell *et al*., 1996; Owen-Smith and Powell, 2004). It has been argued that clusters also give competitive advantage in established industries, however, and many of the clusters that have been taken as evidence for the diamond model are from established industries such as footwear, metal manufacturing (Porter, 2003), shipbuilding, and shipping (Benito *et al*., 2003). High-tech clusters are not especially influential in explaining wages or employment, suggesting that the cluster construct is independent of technology level (Porter, 2003).

The rivalry and supporting-industry mechanisms in cluster theory lead to a prediction on how innovative production technologies will spread. If a firm in the cluster adopts a valuable new production technology, then other firms in the cluster will be quicker to adopt it than firms outside the cluster, because the strong within-cluster rivalry increases awareness of technologies used by nearby firms (Porac *et al*., 1995) and perceived risks of using an older technology (Lieberman and Asaba, 2006). Also, the strong ties between firms in the cluster facilitate innovation diffusion among suppliers and users of production equipment. Thus, the prediction is that firms located in a cluster in which other firms adopt an innovative production technology will be quick to adopt it:

*Hypothesis 2: Firms that are in the same cluster as early adopters of an innovation have a greater likelihood of adopting it.*

Recent work has sought to extend cluster theory in response to critiques. One argument against



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cluster theory is that it is difficult to define meaningful spatial and industrial cluster boundaries (Martin and Sunley, 2003). In practice, clusters tend to be identified as regions that have distinctive groupings of firms that trade with each other or share a common knowledge base, but this definition is better for discovering regional specialization than for adjudicating whether individual firms are members of a given cluster. Firms in clusters defined in this way are not similar to each other, but instead display heterogeneity in their networks (McEvily and Zaheer, 1999; Breschi and Lissoni, 2001), access to external knowledge (Lazerson and Lorenzoni, 1999), and ability to absorb new information (Martin and Sunley, 2003; Giuliani and Bell, 2005). Cluster theorists have noted that ties to firms outside the cluster help cluster firms import useful knowledge (Lazerson and Lorenzoni, 1999; Breschi and Malerba, 2001; Giuliani and Bell, 2005), but have not emphasized the converse implication that such ties also export knowledge from the cluster and thus reduce its distinctiveness. Hence cluster location may be only a partial description of a firm's ability to adopt valuable innovations, as the firm's network position is also very important.

This argument points toward a revised cluster theory that directly examines the links between supplier firms that make production technologies and buyer firms that use it to gain competitive advantage. The theory can be modified by retaining the assumption that innovative production technologies spread from suppliers to users, but discarding the assumption that these network ties are within a spatial cluster. However, this extension leaves open the possibility that valuable innovations spread too quickly to produce competitive advantage. In a model of cluster isolation, firms would gain competitive advantage from being in a cluster that shared all valuable technologies but barred access to outsiders, ensuring that the technologies developed in the cluster would remain rare. Once clusters are connected, however, the spread of valuable technologies no longer has clear limits, and they could lose their rareness. Hence, although network ties can spread valuable innovations, they may end up spreading them so widely that they no longer are a source of competitive advantage. The link from network ties to competitive advantage thus depends on network ties giving early adoption and the speed of diffusion being slow overall. The prediction is:

*Hypothesis 3: Firms that share a supplier with early adopters of an innovation have a greater likelihood of adopting it.*

## Network diffusion and positional advantage

The idea that valuable innovations spread selectively through network ties has been further developed in the theory of network diffusion. Network effects on the diffusion of innovations is a large research tradition built on the idea that network ties transmit information that influence the evaluation of innovations, and thus the likelihood that innovations will be adopted (Strang and Soule, 1998; Brass *et al*., 2004). Diffusion processes that initially are locally bounded often expand beyond the locale (McKendrick *et al*., 2000; Guler, Guillen, and Macpherson, 2002), which seems different from the local diffusion posited by cluster theory. One response to this observation is to examine whether the innovation spreads through clusters of firms that are proximate in network space rather than in geographical space. Network ties can be analyzed directly to find which firms are closer to each other because they are connected to each other, and thus are a cohesive cluster, or are connected to the same third parties, and thus are a structurally equivalent cluster (Burt, 1987; Galaskiewicz and Burt, 1991; Mizruchi and Stearns, 2001). Cohesion allows easy monitoring and maintenance of reputations, which creates trust (Coleman, 1988), while structural equivalence results in role similarity that can trigger rivalry (Burt, 1987). Although there is clear evidence that innovations are imitated more rapidly within cohesive or structurally equivalent clusters, innovations also spread beyond network clusters (Brass *et al*., 2004).

An explanation for broad diffusion can be found in recent theory and research on small-world networks, which contain a mix of locally cohesive network clusters and distant ties so that there is rapid diffusion within the network clusters, but also intercluster ties that let innovations spread from cluster to cluster (Watts, 1999; Barabasi, 2002). Only a few steps are needed to reach all nodes in a small-world network, and thus diffusion can be rapid and complete even when it occurs exclusively through network ties. However, rapid and complete diffusion is still not a necessary outcome of social networks, because many real-world networks do not facilitate long-distance communication as well as small-world networks do (Trusina,



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Rosvall, and Sneppen, 2005). Also, it is not necessarily the case that networks spread innovations through all their ties, because complex information is transferred more easily through ties with high trust or intense social interaction (Hansen, 1999). Indeed, comparison of the diffusion of two governance practices showed that the less controversial practice spread through the national director interlock network, which is a small world (Davis, Yoo, and Baker, 2003), while the more controversial practice spread locally within cities (Davis and Greve, 1997). Thus, network theory is related to the theory of competitive advantage because networks help firms learn about valuable innovations, but many networks are not so highly connected that the innovation loses its rareness.

Predicting innovation diffusion through networks requires identifying network positions that give access to information trusted by the recipient. Production technology innovations with potentially large but uncertain benefits make the problem of trust acute. The suppliers of such innovations are likely to provide biased assessments of innovations, with the bias depending on whether they are able to supply the innovation, and thus seek to market it, or whether they cannot supply it, and thus seek to denigrate it in order to sell the older technology (Cooper and Schendel, 1976). Hence, the diffusion through shared suppliers hypothesized earlier (Hypothesis 3) may fail to occur because managers doubt the reliability of information gained through this route. Also, adopters of a new production technology that gives competitive advantage will try not to inform their competitors about its value, and thus do not have the same proselytizing role as adopters of innovations that provide legitimacy or standardization advantages (DiMaggio and Powell, 1983; Levitt and March, 1988). When any individual source of information about the innovation is suspect, managerial choice of information sources becomes crucial for the decision.

One way to judge the value of innovations is to infer from the fact that an adoption happened that the adopter viewed it as valuable, and thus increase one's own evaluation of it (Bikhchandani, Hirshleifer, and Welch, 1992). When many past adopters exist, those that are most salient and similar to the focal firm will be given greater weight in the decision (Greve, 2005). The key role of suppliers in providing innovative production technologies means that salience and perceived similarity is influenced by whether the firms transact with the same set of suppliers. Firms that transact with the same set of suppliers have access to the same technologies, and may have made similar purchases of production technologies in the past so that their current production systems and routines resemble each other. Thus, they are relevant through having similar external opportunities and internal skills. Such sets of structurally equivalent firms are driven to early adoption of innovations by their rivalry, just as firms in geographical clusters, and gain competitive advantage when the innovations are valuable. Hence, the prediction is:

*Hypothesis 4: Firms are more likely to imitate the innovation adoptions of other firms in the same network cluster in the firm-supplier network.*

Another approach is to compare information from multiple sources. If any individual source of information is uncertain, managers who have access to multiple sources become more confident in their evaluations of innovative technologies. Managers get access to more information when they are central in the network, causing central actors to be early adopters (Coleman *et al.*, 1966; Strang and Tuma, 1993). In addition to this informational reason for central-actor adoption, centrality also has a competitive aspect. Central actors often occupy high positions on status hierarchies and are motivated to maintain these positions through means such as early adoption of innovations (Becker, 1970). These explanations overlap, as the perception of being in a technological race is stronger in a central firm because it more often receives news of adoptions by other firms. These arguments lead to:

*Hypothesis 5: Central firms in the firm-supplier network are more likely to imitate innovation adoptions.*

## Supplier innovations and competitive advantage

Innovations are a source of 'creative destruction' that alter firm competitive strength and industry structure (Schumpeter, 1976). Innovations can incrementally improve the performance of a product relative to its price or create a product with



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radically different characteristics (Dewar and Dutton, 1986). Incremental innovations exploit competencies that are held by the dominant firms in an industry, whereas radical innovations result from technological exploration by outsider firms (Tushman and Anderson, 1986). In both cases, the innovation gives competitive advantage to the adopters in the short run, and can also give competitive advantage in the long run if it spreads slowly. Both incremental and radical innovations are more easily adopted by firms that have greater depth of knowledge (Dewar and Dutton, 1986), but organizations are slow to adopt radical innovations that are incompatible with the current technology, organizational form, or customer preferences (Tushman and Anderson, 1986; Henderson and Clark, 1990; Christensen and Bower, 1996).

Many innovations are made by suppliers rather than by members of the focal industry. Suppliers of capital assets such as production equipment make innovations in production technology, either alone or in cooperation with selected customers, and market the innovations to other firms. If the innovation actually delivers the claimed improvements in the production process, the supplier is effectively selling competitive advantage. Some view 'competitive advantage for sale' as a trivial strategic situation because everyone will rationally buy it, and thus the advantage to the initial adopters will quickly be diluted (Barney, 1986). From the viewpoint of cluster and network theory it is not trivial because there may be uncertainty about the value of the innovation or lack of knowledge on how to apply it, which favors buyers with prior knowledge or an advantageous cluster or network position. Hence, supplier innovations that increase the production efficiency or improve the products of the customer firms are an important test case for the predictions of these theories.

There is evidence for slow diffusion of supplier innovations. The classic Mansfield (1961) study of 12 productivity-increasing innovations showed average times until one-half the firms had adopted ranging from 0.9 to 15 years, with an average of 7.8 years. Later work reported an average of 24 years for a sample of 46 innovations (Gort and Klepper, 1982), and a reanalysis of the subset of 20 production equipment innovations showed that the average time elapsed from 10 to 90 percent adoption rate was 15 years (Jovanovic and Lach, 1997). A comprehensive study of 265 innovations found a mean transition time from 10 to 90 percent adoption rate of 41 years, though with most diffusion processes ranging between 15 and 30 years. Two observations can be made about these studies. First, only Mansfield (1961) and Jovanovic and Lach (1997) had a sample limited to production technology, which is the type of innovation relevant for this argument, while the other studies also had innovations that were final products. Second, the innovations that increased productivity the most spread faster. This may explain why the studies with a greater number of innovations reported slower diffusion, because the studies with few innovations only had very successful ones (Jovanovic and Lach, 1997). Still, these diffusion processes were sufficiently slow to suggest that early adopters of a valuable technology gain competitive advantage because it remains rare for a long time after adoption, so the diffusion of a new production technology determines the distribution of competitive advantage.

Two gaps in this evidence suggest that it is not sufficient to evaluate these theories. First, many of the diffusion processes took place a long time ago. The speed of diffusion may have increased because of changes in the availability of information about innovations, the ability to finance capital investments, and the speed with which early adopters can deploy superior assets to the disadvantage of their competitors. Hence a study of more recent innovations than, for example, the diesel locomotive (Mansfield, 1961) and the transistor (Gort and Klepper, 1982), may be needed to judge whether supplier innovations currently have nontrivial variation in adoption times. Second, these studies examined the aggregate adoption, and thus did not provide evidence on the predictions that the theories make on which firms will be early adopters. To close these gaps, a study of two recent innovations in maritime shipping was conducted.

## INNOVATIONS IN MARITIME SHIPPING

### Maritime shipping

Maritime shipping is the oldest global industry, and is still the main mode of long-distance transportation of goods. The maritime shipping industry is very competitive with average rates of returns below many other industries with similar risks (Stopford, 1997: 69–70). The industry is international, and the pool of firms capable of entering a



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given market niche is large. There are few legal entry restrictions, and there is a broad stock of shipping firms with the necessary capital and operating experience to enter markets they find promising.

Shipping firms deliver transportation services but, as in many other service industries, the service delivery requires substantial investments in capital goods. The merchant ship is the largest means of commercial transportation available. It is built for efficient operation and customized to deliver specific transportation services. The ship types studied here have prices in the range of 25 to 120 million U.S. dollars depending on size and equipment, and have effective lifetimes of 20 years or more. Obtaining the best available ship is important for the long-term services and cost structure of the shipping firm.

This study compares the diffusion of post-Panamax container ships and double-hull oil tankers. These ship designs were selected for study because they are two of the most important recent innovations in shipping, as measured by the number of adoptions. Containers and oil are major markets in shipping, so innovations directed toward these markets affect the competitive advantage of many firms. Each of these innovations provides advantages to the owners, though there is sufficient uncertainty about their value to make the adoption risky. The buyers of post-Panamax container ships are sacrificing flexibility for efficiency, while the buyers of double-hull tankers are betting on nations maintaining or tightening their rules for preventing oil spills. Despite the uncertainty, these innovations are successful and are thought to provide competitive advantage to their owners over their effective lifetimes.

Indeed, performance data were available for some of the firms in the sample, and suggested that the firms that adopted these innovations were more profitable. A total of 281 years of accounting data were available from 31 container lines that ranged from zero to 76 percent adoption of post-Panamax ships. In this sample, the proportion of post-Panamax ships was positively related to return on assets (ROA) at the 0.01 level of significance. Likewise, a total of 381 years of accounting data were available for 43 firms operating oil tankers that ranged from zero to 100 percent adoption of double-hull tankers. In this sample, there was no direct relationship between double-hull tankers and ROA, but an interaction of the proportion of double-hull tankers and the proportion of tankers in the fleet was positively related to ROA at the 0.05 significance level. Hence, double-hull oil tankers increased profitability for the firms with greater commitment to the tanker market. Although these figures are suggestive, the scarcity of firms with available accounts indicates that they should be interpreted with caution.

### *Post-Panamax container ships*

Container shipping is the main segment of liner shipping with predetermined routes and regular port calls. Specialized container ships is currently the most cost-efficient mode of transportation available for cargoes that fit into standard-sized containers and are transported in lots less than an entire ship (Stopford, 1997). Modern container shipping is an integrated system, however, where sea and land modes of transportation are managed jointly to minimize the travel cost between destinations.

The post-Panamax container ship was an important innovation in container shipping. Panamax ships can go through the Panama Canal, and have maximal dimensions of 294 meters long, 32.3 meters wide, and 12.04 meters draught. This is important for ships servicing routes such as Asia to the east coast of North America, because they would otherwise have to go around Cape Horn or unload containers bound for the east coast to rail links on the west coast. Even ships servicing other routes were initially held to Panamax sizes in order to allow flexible allocation of ships to routes. Panamax ships were limited to about 4,000 TEU (Twenty-Foot Equivalent Unit), which is the capacity of a standard height 20-foot container. The first post-Panamax ships were ordered in 1987 by APL (USA), and built in Howaltswerke Kiel (Germany). In April 2005, 697 post-Panamax container ships were in operation, being built, or on order.

The advantage offered by the post-Panamax ship is lower cost. For any ship type, larger ships are more efficient when all costs (investment, operating, loading/discharge, port fees) are taken into consideration, in large part because they are more fuel efficient. During the study period, ship prices also increased less than proportionally to the size, but this relation depends on the supply-demand balance and is thus more volatile. The total cost advantage is a function of the costs at sea, reloading time in port, and typical load factor, which



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sum up to savings per container of 13.5 percent on a transpacific route and 16 percent on an Asia-Europe route when replacing two 4,000 TEU ships with an 8,000 TEU ship (Cullinane and Khanna, 1999). The differences are greater now because fuel prices have risen since these estimates were made. When firms having unequal ship sizes compete, the firm with smaller ships can increase port calls and sailing frequencies to offset its cost disadvantage, but with current cost structures this countermove is ineffective in Asia-Europe routes and only marginally effective in transpacific routes (Imai *et al*., 2006). As a result of these cost advantages, post-Panamax container ships have grown from an initial size of 4,300 TEU to a current maximum of 13,500 TEU.

For the shipbuilder, the main difficulty in building post-Panamax ships is a hull flexibility problem shared by all container ships, but made worse in large ships. The wide hatches give container ships low structural rigidity, so they flex with the sea motion. This causes wear on the lashing posts that hold the containers in place on deck and can induce parametric rolling, which is a violent pitching and rolling motion that in one case led to the loss of most containers on deck and serious damage to the ship. For shipping firms, post-Panamax ships are easy to operate, but require two types of additional investments. First, shipping lines need to establish sea and land feeder routes to allow the fewer port calls that are needed for full utilization of large ships. Second, ports need to invest in cranes with a greater reach than those used for Panamax ships. Both types of investment have proceeded quickly, with port operators being forced to buy new cranes because they compete with other ports for becoming the destination of the largest ships (McCalla, 1999).

### *Double-hull tankers*

Bulk shipping is when the cargo fills the ship or a significant portion of it on a journey ordered by the customer rather than on a route serviced by the shipping firm. An important segment in modern bulk shipping is oil shipping. Oil tankers carry crude oil, product (refined oil), or product and chemicals carried in separate tanks. Oil tankers carry crude oil on the main routes between producing and consuming nations, distribute crude oil from receiving terminals to refineries, and distribute product from refineries to markets. Oil tankers are booked in the spot market or as time charters. Large oil tankers are more efficient than small ones, but the largest types are no longer built because high oil prices make them difficult to insure.

Double-hull oil tankers increase the environmental safety by reducing the potential for oil spills as a result of collisions or groundings. Keystone Alaska (U.S.A) had three double-hull crude oil tankers built at the Sun Shipyard (U.S.A) from 1975 to 1979, but the design was not adopted by other firms because of cost considerations (Spyrou, 2006). The *Exxon Valdez* accident in 1989 led to a reexamination of the pollution hazards involved in operating single-hull oil tankers near the coast. In response, the U.S. Oil Pollution Act (OPA) of 1990 sharpened liability rules and mandated a gradual conversion to double-hull tankers, and the MARPOL (short for marine pollution) International Convention for the Prevention of Pollution from Ships mandated a gradual conversion to double-hull tankers for traffic to ports in 1992. The MARPOL rules were made stricter in 2003 as a result of the *Erika* accident off the coast of France in December 1999. Although these rules still allow single-hull tankers to operate for a while and have some loopholes,[1] shipping managers have noticed that they become more restrictive following large oil spills. In June 2005 more than 2,000 double-hull tankers were in operation, being built, or on order.

Because double-hull tankers are a mandated solution to the pollution problem, they have a more complex relation to competitive advantage than post-Panamax ships. Eventually all the old single-hull ships will be scrapped or converted to safer designs, so this innovation will lose rareness. However, there are two advantages to early adoption. First, the safety characteristics of both single and double-hull tankers deteriorate if they are not maintained correctly, and double-hull tankers have sufficiently different maintenance requirements that shipping firms need to develop new routines for them. For example, a unique concern for double-hull tankers is material fatigue near the

[1] The MARPOL convention is not enforced in all nations; it allows operation of existing single-hull tankers with certain restrictions and retrofitting of a double hull to single-hull tankers; it allows alternative designs with the same safety properties as a double hull; and nations may choose not to apply the rules to offshore tendering terminals (used to discharge oil from ships for which regular ports are too shallow).

struts holding the tanks, which may lead to oil vapor buildup in the space between the hulls and danger of explosion. Second, when many shipping firms delay acquisition of double-hull tankers, the result is last-minute congestion of orders that drives up building costs and leaves late adopters with a cost disadvantage. Because firms that were late in replacing their single-hull tankers placed their orders while other shipping markets were booming, the congestion problem became serious, leading to a 60 percent price increase in new oil tankers from January 2003 to October 2004. Used oil tankers had a similar price increase, so firms that replaced their tankers after January 2003 were left with higher capital costs for the same type of tanker.

Double-hull tankers do not require significant technological advances. The double-hull design has long been used for product and chemical tankers, which have smaller tanks than crude oil tankers, so the engineering problems are related to the greater size of each tank in double-hull oil tankers. For shipbuilders, the major challenges are in understanding how the more complex hull structure responds to stresses at sea, but the extra stiffness of the double hull makes this ship type robust. For shipping firms, an important concern in operation is the lower stability of the double-hull tanker, which has a higher center of gravity than single-hull tankers and greater susceptibility to sloshing if the tanks are not full.[2] A double-hull tanker can capsize, which would be a very unlikely event for a single-hull tanker.

## Data and methodology

Data on ships and shipping firms were obtained from the Lloyds Fairplay Enhanced Registry of Ships CD-ROM and a specially ordered download of the Lloyds Fairplay historical ownership data of ships. Lloyds Fairplay keeps track of all ships that have or will get an International Maritime Organization (IMO) number, and has data on ownership, management, shipbuilder, ship construction, and capabilities. Shipping corporations have complex structures that often include separate ship-owning corporations for tax or financing reasons and also split the commercial control from the daily management of crewing, operating, and bunkering. Accordingly, the Lloyds data on fleet ownership and control was used to identify the firms controlling the ships.

The data track each diffusion process from the start. For the post-Panamax analysis, the data are from 1986 through 2004 (19 years), and the population at risk has 580 firms (all firms owning at least one container ship of more than 1,000 deadweight tons). For the double-hull tanker analysis, the data are from 1990 through 2004 (15 years), and the population at risk has 707 firms (all firms owning at least one tanker of more than 1,000 deadweight tons). The risk set contains all firms that are at risk of adopting because they already operate ships using the older technology except those that operate very small ships. Firms entering the focal type of shipping by acquiring the innovative ship type (e.g., when a firm that does not own an oil tanker buys a double-hull tanker) will not appear in the analysis, so the analysis cannot be used to examine when entrants will exploit an innovation. This limitation was inconsequential for the post-Panamax ships because all orders were placed by incumbents, and had little effect on double-hull tankers, where incumbents placed 1,057 of the 1,107 orders. The influence of orders by entrants on incumbent adoptions was controlled by including them in the analysis with a weight of zero (Greve, Tuma, and Strang, 2001).

### Dependent variable and model

The dependent variable is the event of placing an order for an innovative ship type. Shipping firms typically place orders for multiple ships at a time, with staggered deliveries and the last part of the order having the form of an option. It would be artificial to regard each ship as an adoption, because it is the order that corresponds to a decision to acquire one or more ships. The data report order and building dates to the nearest month, and all ships ordered by the same shipper in the same month are assumed to be a single order, so there are fewer events than there are ships. The data do not tell when an option was exercised, so a ship ordered on option will have the same order date as one that was firmly ordered in the same contract. Because Hypothesis 1 concerns the effect of having adopted an innovation on subsequent acquisition, firms that have ordered an innovative ship

[2] Sloshing of oil in the tanks can destabilize a tanker if it is amplified by the waves. More generally, cargo movement has been the bane of many ships and is a constant concern of marine architects.

type are retained in the data. This is different from diffusion studies that only examine first-adoption events, but similar to work on the diffusion of strategies that can be adopted in multiple markets (Greve, 1998).

The data were analyzed by the heterogeneous diffusion model. This model specifies a hazard rate of adoption that depends on the firm's propensity to adopt independent of social influences, susceptibility to influence from other adopters, and social proximity to previous adopters (Strang and Tuma, 1993; Greve, Strang, and Tuma, 1995). It is especially well-suited for analyzing network effects on diffusion because it can incorporate measures of structural equivalence as social proximity effects, and measures of network centrality as effects on the susceptibility to influence. The heterogeneous diffusion model has been used in earlier studies of diffusion through social networks (e.g., Strang and Tuma, 1993; Davis and Greve, 1997; Greve, 1998; Rao *et al*., 2000; Strang, 2003).

The model is specified as follows. Let $X_n$ be a vector of propensity variables, $V_n$ be susceptibility variables, and $Z_{ns}$ be social proximity variables. Let S(t) be the set of prior adopters, who potentially influence the focal firm. Then the hazard rate $r_n(t)$ of a firm *n* adopting an innovation equals:

$$r_n(t) = \exp\{\alpha' X_n\} + \exp\{\beta' V_n\} \sum_{s \in S(t)} \exp\{\delta' Z_{ns}\}$$

In other words, the influence of the earlier innovations is made dependent on the social proximity of the focal firm and the earlier adopter (with coefficients $\delta$), and the sum of influence is multiplied with the susceptibility of the focal firm (coefficients $\beta$). This is added to the propensity (coefficients $\alpha$).

## Network variables

The supplier-buyer network was constructed by defining a tie between a shipping firm and a shipbuilder if the shipping firm owned a ship constructed by the builder. This network is time-varying as firms acquire and sell ships, and the network variables are updated annually. The affiliation network between shipbuilders and shipping firms was converted to a network of shipping firms by letting all shipping firms with a shared tie to a shipbuilder be tied to each other. Three network measures were constructed. The first is the degree share (the number of received ties divided by the total number of received ties in the population), which measures centrality in the network. Degree is the simplest measure of network centrality, and is a good measure for capturing processes in which multiple actors are potential information spreaders, so that the chance of receiving a given piece of information in the next period is proportional to the number of ties to other actors (Borgatti, 2005). The second is a CONCOR computation of clusters with a partition depth of three (giving a maximum of eight clusters). This partitions networks into sets of nodes that share ties with the same group of actors, and thus creates clusters according to the structural equivalence of the nodes. The third is a list of shipping firms with which the focal shipping firm shares suppliers. In the analysis, the centrality affects the susceptibility to adopting the innovation (central firms adopt faster) and the cluster and direct ties affect the social proximity (same-cluster or directly tied firms are more influential). The network analysis was conducted with Ucinet 6 (Borgatti, Everett, and Freeman, 2002).

Because the networks were time varying, two adaptations of the network methods were made. First, count and share measures of ties are equivalent to each other in a time-constant network, but in a time-varying network they are different. The density of the networks increased in the neighborhood of the shipbuilders that were building the innovative ship type, so a share measure of centrality was used to avoid a trend effect. Second, in a time-varying network a cluster analysis may yield different clusters at different times, or may assign different numbers to the same clusters. Hence each cluster analysis was compared with the previous one, and the cluster numbers were adjusted if the analysis had switched cluster numbers, a cluster had dissolved, or a new cluster had appeared. Most clusters persisted over time although there was some exchange of membership.

## Control variables

Macroeconomic statistics can affect ship orders because shipping rates depend on the world economic development as well as changes in the production and use of commodities and finished products. Shipping markets have cycles of under- and oversupply with a rough average of seven years per cycle (Stopford, 1997), but the cycle length is sufficiently variable to make a strategy



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of ordering ships ahead of a turn-up very difficult to implement. Despite this caveat, it is likely that some effect of the economic conditions on ship orders will be seen. In order to control for this, statistics on economic activity and freight rates were collected from the *Shipping Statistics Yearbook* (ISL, 2004) (Institute for Shipping Economics and Logistics), and economic growth data were collected from the Organisation for Economic Co-operation and Development (OECD) files. The specific variables used in each regression were adapted to the economic characteristics of each type of shipping.

The following annually updated variables were used in the analyses. The OECD growth rate is the annual growth rate of the 15-nation OECD region. These nations greatly influence world trade, so their growth can be used to anticipate shipping demand. Crude oil traffic is the worldwide transport of crude oil in billion ton-miles, and is entered into the tanker analysis. Container traffic is the number of containers handled in the world's 38 largest container ports expressed in million TEU, and is entered into the post-Panamax analysis. New crude carrier price is the average price of a 45.000 deadweight ton[3] crude oil carrier, and is entered into the tanker analysis. New bulk carrier price is the average price of a 74.000 deadweight ton bulk carrier, and is entered into the post-Panamax analysis. Bulk carrier prices are available for a longer time than container ship prices, and this ship type is so large that the price reflects the demand/supply balance in the shipyards that build post-Panamax container ships. The prices of similarly sized ships are related because shipyards choose which type to build, but ships of the same type and different size may have diverging prices because small shipyards cannot build large ships. Ship prices are on a unit of a million U.S. dollars.

The following variables vary by firm and year. Firm size is the logarithm of the sum of the deadweight tons of all ships controlled by the firm. Firm age is the number of years since the founding of the firm. Average ship size is the logarithm of the average ship size owned by the focal firm (in deadweight tons). Firm proportion of the focal ship type is based on the size expressed in deadweight tons, and measures the specialization in the focal type of shipping. Firm proportion of old ships is the proportion of tonnage in ships 20 years or older, and measures the replacement need. Ship type diversity is the Herfindahl index of ship types (in deadweight tons) owned by the focal firm. The ship classification is based on the Lloyds Fairplay ship types and has the nine categories bulk, container, cruise, general cargo, offshore, passenger, tanker, vehicle carrier, and others. All independent variables were lagged by one year. The descriptive statistics and correlations for the data are given in Table 1.

## FINDINGS

### Network analysis

Visual inspection of the oil tanker network is not informative because there are too many nodes and relations, but the container network has a manageable size. Figure 1 shows the network of container shipping firms and shipbuilders in 1994. The shipbuilders are squares labeled with abbreviated names, and the shipping firms are marked with symbols indicating cluster assignment. Only shipping firms that had adopted by 1994 are named; the rest are numbered. The graph is made by NetDraw (Borgatti *et al*., 2002), which arranges the firms so that the network links are kept short without placing firms too close to each other. This is done by placing highly interconnected firms near each other, so proximity in the graph reflects network proximity. Three early adopters are affiliated with a shipbuilder—Hanjin, Hyundai, and Maersk (with Odense)—but all are located some distance away from their partner because the shipping firms also buy from other builders and the shipbuilders also sell to many other shipping firms. Ownership ties did not appear to affect the diffusion. All early adopters except the very first (APL) are located centrally in the network. Thus a peripheral actor was the first adopter, and central actors quickly imitated it, as others have observed for important innovations (Leblebici *et al*., 1991).

The nationality of the shipbuilders had little effect on their network location. Three European yards are isolated in the top, but two others are found near Asian yards. Of the European yards, Sietas had a unique network position as a center of its own cluster, but it did not build any post-Panamax ships and thus was not influential in

[3] Deadweight does not measure the weight of a ship, but the volume that it encloses. No measures of ship size are fully comparable across different types of ships, but deadweight is considered the best.



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Table 1. Descriptive statistics and correlation coefficients

| Variable | Mean | Std. Dev. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Container ships:* | | | | | | | | | | | | | |
| 1 Adoption | .027 | .162 | 1.00 | | | | | | | | | | |
| 2 OECD area growth | .022 | .023 | .00 | 1.00 | | | | | | | | | |
| 3 Container traffic | 103.142 | 29.274 | .15 | −.17 | 1.00 | | | | | | | | |
| 4 New bulk carrier price | 41.295 | 4.371 | −.07 | −.14 | −.31 | 1.00 | | | | | | | |
| 5 Firm age | 19.357 | 24.152 | .11 | −.03 | .14 | −.04 | 1.00 | | | | | | |
| 6 Firm size | 9.742 | 3.817 | .17 | −.03 | .21 | −.10 | .06 | 1.00 | | | | | |
| 7 Average ship size | 8.387 | 3.044 | .11 | −.03 | .19 | −.09 | .00 | .95 | 1.00 | | | | |
| 8 Proportion container | .481 | .422 | .08 | −.02 | .16 | −.08 | −.01 | .21 | .34 | 1.00 | | | |
| 9 Proportion old contain. | .137 | .318 | −.02 | −.06 | .26 | −.10 | .02 | .05 | .07 | .20 | 1.00 | | |
| 10 Ship type diversity | .799 | .234 | −.03 | .02 | −.11 | .05 | −.02 | −.48 | −.34 | .26 | .00 | 1.00 | |
| 11 Prior adoption | .042 | .200 | .60 | −.03 | .19 | −.07 | .10 | .23 | .15 | .08 | −.04 | −.07 | 1.00 |
| 12 Network centrality | .002 | .004 | .22 | .01 | −.02 | .01 | .07 | .43 | .30 | −.08 | −.10 | −.29 | .30 |
| *Tankers:* | | | | | | | | | | | | | |
| 1 Adoption | .110 | .313 | 1.00 | | | | | | | | | | |
| 2 OECD area growth | .018 | .023 | .01 | 1.00 | | | | | | | | | |
| 3 Crude oil traffic | 7586.264 | 558.704 | .29 | .22 | 1.00 | | | | | | | | |
| 4 New tanker price | 29.820 | 3.968 | −.30 | −.14 | −.79 | 1.00 | | | | | | | |
| 5 Firm age | 18.982 | 22.978 | .21 | .02 | .19 | −.15 | 1.00 | | | | | | |
| 6 Firm size | 11.190 | 2.022 | .29 | .00 | .10 | −.09 | .21 | 1.00 | | | | | |
| 7 Average ship size | 9.417 | 1.349 | .22 | .00 | −.02 | .01 | .13 | .87 | 1.00 | | | | |
| 8 Proportion tankers | .807 | .302 | −.07 | .00 | −.02 | .01 | −.05 | −.43 | −.27 | 1.00 | | | |
| 9 Proportion old tankers | .259 | .363 | −.04 | .02 | .29 | −.23 | −.03 | −.08 | −.07 | .11 | 1.00 | | |
| 10 Ship type diversity | .845 | .223 | −.12 | −.00 | −.03 | .02 | −.08 | −.48 | −.27 | .82 | .08 | 1.00 | |
| 11 Prior adoption | .272 | .445 | .39 | −.04 | .25 | −.20 | .14 | .22 | .19 | −.01 | −.04 | −.06 | 1.00 |
| 12 Network centrality | .0014 | .0022 | .23 | .00 | .05 | −.05 | .10 | .65 | .45 | −.28 | −.14 | −.36 | .14 |

spreading this innovation. Two Chinese yards are in the bottom of the graph, but a third is near Kawasaki (Japan) and Odense (Denmark). The Japanese and Korean yards are intermingled.

Spatial analysis of the network ties yield evidence on the role of location in the supplier-buyer network, and can indicate whether network ties are contained within spatial clusters. A local affiliation preference would be evident if shipbuilders had a high proportion of domestic ties and few distant ones. In the container network, builders had ties with shipping firms from 8.5 nations on average, and 30 percent of the ties were domestic, showing an abundance of cross-national ties. On average, a container ship has an owner 2,277 miles away from the shipyard. The distance from Tokyo to Los Angeles is 5,433, and from Tokyo to London is 5,960 miles, so this suggests that many purchases are cross-continental. In the tanker network, each builder had ties with shipping firms from 7.1 nations and 31 percent domestic ties. On average, a tanker has an owner 3,576 miles away from the shipyard. The conclusion from these statistics is clear. Although location near a shipbuilder allows early access to knowledge about an innovation, many spatially dispersed shipping firms learn about the innovation if the shipbuilder markets it through its network of existing customers. However, the actual sales of innovative ship types are much more local. A post-Panamax container ship is on average sold to an owner 1,176 miles away from the shipyard, and a double-hull tanker is sold to an owner 2,028 miles away. Thus the overall network is dispersed, but innovation diffusion occurs along more spatially proximate ties. The diffusion analysis will reexamine this conclusion by comparing geographical and network determinants of adoption.

## Aggregate diffusion

Graphs of these diffusion processes help evaluate whether the innovations spread slowly enough to give early adopters competitive advantage. One would expect rapid diffusion if the managers of all firms simultaneously realized that an innovation gave competitive advantage and moved to obtain it, while uncertainty regarding its value would slow down the diffusion and increase the

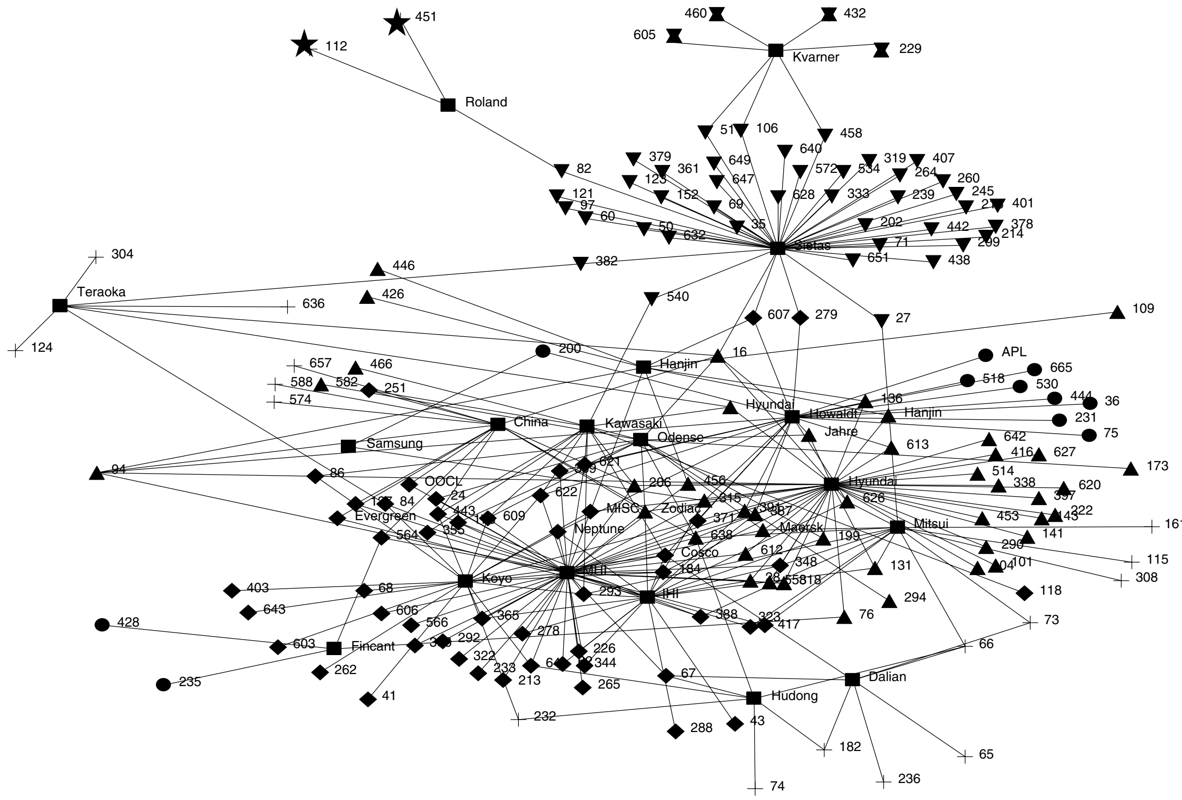


Figure 1. 1994 container network

advantage accrued to the early adopters. Capacity constraints in producing the innovation delays the diffusion when deliveries are measured, but these data show orders and can thus give an arbitrarily steep curve. Figures 2a and 2b show the diffusion of the two innovations. The horizontal axis is the date, and the vertical axis is the cumulative proportion of adopting firms. The diffusion of the double-hull tanker had a rapid climb that started in the year 2000, while the rules regarding double hulls were imposed in 1992. There were still many oil-shipping firms that did not own double-hull tankers at the end of this diffusion curve. In June 2005, one-third of all oil tankers in use had double hulls, but two-thirds of all firms operating oil tankers had no double-hull tankers at all. The post-Panamax container figure shows a gradual diffusion process, which is surprisingly slow given the great efficiency increase of these ships, and gives a lengthy period of cost advantages for the early adopters. The cumulative adoption proportion is also low, but this could be because of firm heterogeneity. Not all firms service routes with sufficient traffic to justify post-Pamamax container ships, so it is unclear what adoption proportion would constitute full adoption by all firms operating eligible routes. Thus, these innovations initially failed to spread as widely as they would later, and this partial diffusion gave the early adopters an advantage.

### *Post-Panamax container ships*

The findings on innovation diffusion are displayed in Tables 2 and 3. Table 2 shows the analysis of the diffusion of post-Panamax container ships. The variables are entered in groups according to theory, and finally all are entered jointly. Because the network and cluster variables might have overlapping effects, they were also entered one by one in preliminary analyses, but all findings from these analyses were reproduced in models shown in the table. Model 1 shows that post-Panamax container ship building was greater following years with high OECD area growth and high container traffic and lower when ship prices were high. Large and specialized container shipping firms were more likely to buy post-Panamax container ships, as expected

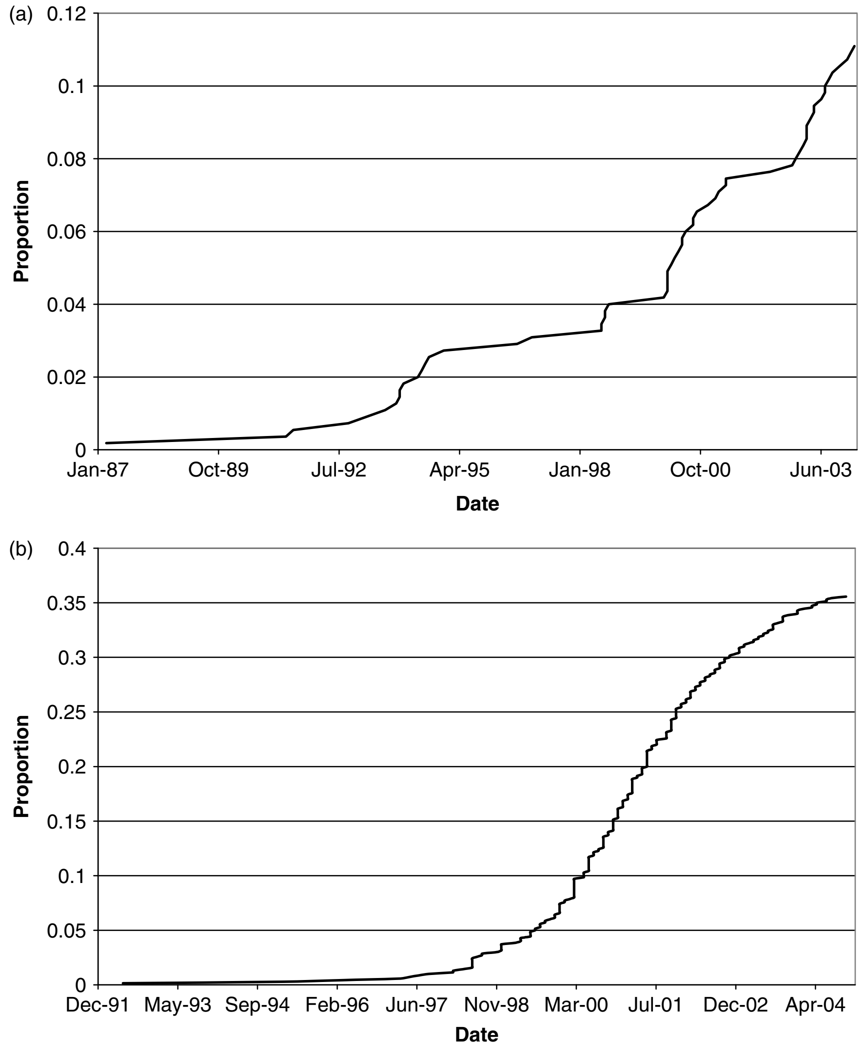


Figure 2. (a) Post-Panamax container ship adoption. (b) Double-hull tanker adoption

given the significant commitment of resources required to buy and operate them, and so were firms with high average ship size. Old firms were less susceptible to influence from prior adopters, and firms with old ships appeared disinclined to replace them with post-Panamax ships.

Model 2 adds the indicator variable for prior adoption of a post-Pamamax container ship, and shows a significant and positive coefficient in support of Hypothesis 1. Hence, adopters appear to build on their advantage by making additional orders. A possible caution against this interpretation is that it is not clear that firm accumulation of experience with the new ship type causes the next order, as firms have been observed repeating strategic decisions before obtaining sufficient feedback to evaluate their success (March, Sproull, and Tamuz, 1991). A reason to believe that some learning has occurred is that ship orders tend to be for multiple ships delivered over some stretch of time (e.g., five ships delivered over three years), so firms have experience with the first ships in a new series when making a second order.

Model 3 replaces these variables with the cluster-theory variables for whether the firm is in a different nation than past adopters or has connections to the same builders. The different-nation coefficient is negative and significant, giving support for Hypothesis 2 that innovations have more rapid spread within nations. The same-builder coefficient is not significant, and thus the prediction that direct ties to builders spread innovations



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Table 2. Diffusion of post-Panamax container ships

| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
|---|---|---|---|---|---|
| *Propensity* | | | | | |
| Intercept | −29.930 | −18.060 | −29.220 | −29.810 | −18.860 |
| | (1.774) | (1.882) | (1.779) | (1.830) | (1.929) |
| OECD area growth rate | 10.130** | 10.630** | 10.170** | 10.660** | 10.790** |
| | (3.094) | (3.113) | (3.099) | (3.161) | (3.159) |
| Container traffic | 0.015** | 0.007** | 0.015** | 0.015** | 0.007** |
| | (0.002) | (0.002) | (0.002) | (0.002) | (0.002) |
| New bulk carrier price | −0.057** | −0.048** | −0.058** | −0.053** | −0.045** |
| | (0.014) | (0.015) | (0.014) | (0.014) | (0.015) |
| Firm age | 0.0068** | 0.0069** | 0.0069* | 0.0074** | 0.0073** |
| | (0.0020) | (0.0020) | (0.0020) | (0.0020) | (0.0020) |
| Firm size | 0.934** | 0.573** | 0.934** | 0.951** | 0.596** |
| | (0.066) | (0.069) | (0.066) | (0.067) | (0.071) |
| Average ship size | 1.035** | 0.402* | 1.035** | 1.050** | 0.416* |
| | (0.184) | (0.185) | (0.184) | (0.188) | (0.187) |
| Proportion container ships | 3.134** | 1.718** | 3.134** | 3.116** | 1.739** |
| | (0.324) | (0.353) | (0.324) | (0.326) | (0.354) |
| Proportion old container ships | −0.988* | −0.507 | −0.998** | −0.906* | −0.445 |
| | (0.392) | (0.400) | (0.395) | (0.389) | (0.398) |
| Ship type Herfindahl | −1.043* | −0.247 | −1.042* | −1.205* | −0.343 |
| | (0.478) | (0.489) | (0.479) | (0.485) | (0.489) |
| Prior adoption | | 2.310** | | | 2.259** |
| | | (0.216) | | | (0.219) |
| *Susceptibility* | | | | | |
| Intercept | −11.520 | −11.160 | −7.731 | −5.749 | −3.237 |
| | (0.825) | (0.820) | (2.885) | (0.744) | (1.566) |
| Firm age | −0.244* | −0.328* | −0.218+ | −0.310** | −0.368** |
| | (0.112) | (0.161) | (0.126) | (0.098) | (0.137) |
| Degree share | | | | −130.7* | −89.80+ |
| | | | | (66.27) | (53.81) |
| *Social proximity* | | | | | |
| Different nation | | | −2.926* | | −3.631** |
| | | | (1.407) | | (1.312) |
| Same builder | | | −2.071 | | −6.870 |
| | | | (4.125) | | (49.53) |
| Different network cluster | | | | −5.445** | −5.370** |
| | | | | (0.793) | (1.276) |
| Model log likelihood | −1272.09 | −1202.08 | −1270.79 | −1266.79 | −1199.51 |
| Likelihood ratio test against model 1 (d.f.) | | 140.02** | 2.60 | 10.60** | 145.16** |
| | | 1 | 2 | 2 | 5 |

+ $p < 0.10$; * $p < 0.05$; ** $p < 0.01$, two-sided z tests.
256 events for a total of 697 ships built or on order. Standard errors are in parentheses below each coefficient estimate. Likelihood ratio tests are given for improvement relative to Model 1.

is not supported. For this innovation, the conventional cluster theory has better support than the extended one.

Model 4 replaces the cluster theory variables with network theory variables for centrality and different network cluster. The different-cluster variable has a negative and significant coefficient estimate, in support of Hypothesis 4 of more rapid diffusion within clusters of structurally equivalent firms. The degree share has a negative and significant coefficient estimate, contrary to the prediction in Hypothesis 5. Hence the structural equivalence prediction is supported, but the centrality prediction is contradicted. The latter finding could mean that firms with many network contacts pay less attention to each one, thus partially canceling their positional advantage. Model 5 enters all variables jointly, and shows clear support for Hypothesis 1 of repeated adoption, Hypothesis 2 of rapid diffusion within nations, and Hypothesis

Table 3. Diffusion of double-hull tankers

| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
|---|---|---|---|---|---|
| *Propensity* | | | | | |
| Intercept | −24.660 | −19.560 | −23.810 | −21.070 | −18.290 |
| | (1.899) | (1.469) | (2.089) | (2.605) | (1.740) |
| OECD area growth rate | 11.520** | 11.520** | 12.980** | 17.720** | 13.180** |
| | (2.102) | (1.704) | (2.400) | (3.314) | (2.033) |
| Crude oil traffic | 0.0024** | 0.0019** | 0.0024** | 0.0022** | 0.0019** |
| | (0.0002) | (0.0002) | (0.0002) | (0.0003) | (0.0002) |
| New crude carrier price | −0.267** | −0.237** | −0.286** | −0.333** | −0.261** |
| | (0.021) | (0.016) | (0.024) | (0.031) | (0.020) |
| Firm age | 0.0043* | 0.0049** | 0.0049** | 0.0023 | 0.0029 |
| | (0.0018) | (0.0014) | (0.0018) | (0.0023) | (0.0018) |
| Firm size | 0.665** | 0.390** | 0.643** | 0.630** | 0.368** |
| | (0.048) | (0.040) | (0.051) | (0.058) | (0.046) |
| Average ship size | −0.104 | 0.013 | −0.107 | −0.111 | 0.013 |
| | (0.065) | (0.055) | (0.067) | (0.077) | (0.061) |
| Proportion tankers | 1.340** | 0.610** | 1.349** | 1.559** | 0.650** |
| | (0.245) | (0.188) | (0.258) | (0.317) | (0.216) |
| Proportion old tankers | −0.892** | −0.509** | −0.969** | −1.016** | −0.533** |
| | (0.181) | (0.155) | (0.191) | (0.216) | (0.173) |
| Ship type Herfindahl | −0.660* | −0.460+ | −0.608+ | −0.626+ | −0.377 |
| | (0.301) | (0.251) | (0.317) | (0.379) | (0.289) |
| Prior adoption | | 1.575** | | | 1.619** |
| | | (0.093) | | | (0.101) |
| *Susceptibility* | | | | | |
| Intercept | −11.840 | −12.860 | −10.530 | −10.360 | −22.990 |
| | (0.148) | (0.325) | (0.353) | (0.224) | (49.420) |
| Firm age | 0.017** | 0.020** | 0.015** | 0.016** | 0.019** |
| | (0.003) | (0.005) | (0.003) | (0.002) | (0.003) |
| Degree share | | | | 106.7** | 155.70** |
| | | | | (29.16) | (45.80) |
| *Social proximity* | | | | | |
| Different nation | | | −1.518** | | 11.880 |
| | | | (0.448) | | (49.420) |
| Same builder | | | 1.803** | | −14.430 |
| | | | (0.367) | | (65.030) |
| Different network cluster | | | | −1.722** | −1.912** |
| | | | | (0.286) | (0.482) |
| Model log likelihood | −4794.11 | −4624.06 | −4790.32 | −4776.77 | −4612.59 |
| Likelihood ratio test | | 340.1** | 7.58* | 34.68** | 363.04** |
| against model 1 (d.f.) | | 1 | 2 | 2 | 5 |

+ $p < 0.10$; * $p < 0.05$; ** $p < 0.01$, two-sided z tests.
1,057 events for a total of 1,810 ships ordered. Standard errors are in parentheses below each coefficient estimate. Likelihood ratio tests are given for improvement relative to Model 1.

4 of rapid diffusion within clusters of structurally equivalent firms. One prediction from each theoretical perspective is thus supported, as the diffusion process is affected by proximity in both geographical and network space, as well as by prior experience with the innovation.

The findings strongly suggest that firms gain competitive advantage from being near early adopters of valuable innovations either in geographical space or in the network of supplier-buyer relations. Long distance from early adopters makes the value of the innovation seem less certain, which is a barrier against adoption—even when the innovation is valuable and available for purchase, and news of the adoption is spread widely. Similarly, competitive advantage is also gained from network contacts, but not from a tie with a supplier that has provided the innovation to others. Such a tie still leaves doubt about whether the innovation is as valuable as the supplier claims, whereas sharing a network cluster with other adopters makes the value of adoption more compelling. The diffusion of innovations that give competitive advantage is spurred by close rivalries, and prevented by distance.

*Double-hull tankers*

Table 3 shows the analysis of the diffusion of double-hull tankers. Model 1 shows that the OECD area growth rate and crude traffic positively influenced the rate of ordering double-hull tankers, and ship prices had a negative effect. Firm size and specialization had positive effects on the propensity to adopt, as expected. The findings on propensity are thus similar to those of the post-Panamax diffusion. Firm age had a positive effect on susceptibility, which is opposite of the post-Panamax analysis.

Model 2 enters the indicator for prior adoption, and finds a positive and significant coefficient in support of Hypothesis 1. This is exactly as in Model 2 for the post-Pamamax ships. Model 3 enters variables for having contact with the same builder and being located in a different nation. The estimates show a significant negative effect of location in a different nation, as predicted by Hypothesis 2, and a significant positive effect of owning ships from the same builder, consistent with Hypothesis 3. Thus, the estimates give full support to cluster theory.

Model 4 enters variables for different-cluster location and network centrality. The coefficient estimate for different network cluster is negative and significant, lending support to Hypothesis 4 on imitation of structurally equivalent firms. The coefficient estimate for centrality is positive and significant, unlike the negative effect in the analysis of container ships, and gives support for Hypothesis 5 on a centrality effect. Network theory is thus fully supported as well. Model 5 enters all variables at once, which causes loss of significance in the variables for different nation (Hypothesis 2) and same builder (Hypothesis 3). Hence, the partial models show support for all predictions individually, but the full model supports only the predictions from network theory.

The findings show that sharing a network cluster with other adopters makes the value of adoption more compelling, just as in the post-Panamax diffusion. In addition, central firms in the supplier-customer network became earlier adopters, so adoption of innovations that give competitive advantage is spurred by close rivalry and broad contacts. The findings across these two innovations are remarkably similar considering the difference in the markets and in the source of their advantage. While post-Panamax ships exploit scale advantages, the value of double-hull tankers was legislated into existence with the 1990/1992 decisions to gradually reduce market access for single-hull tankers. Despite these differences, the diffusion processes were much the same, including a lengthy latency period from the 1992 legislation to the upswing in orders.

## DISCUSSION

### Theoretical implications

This investigation started with the question: When do valuable innovations spread so slowly and selectively that they give competitive advantage to early adopters? The traditional view has been that either tacit knowledge or complexity is a necessary condition for slow diffusion, because only then is it imperfectly imitable (Lippman and Rumelt, 1982; Reed and DeFillippi, 1990; Barney, 1991; Kogut and Zander, 1992). These arguments place the explanatory power on the difficulty of obtaining the innovation and using it effectively, and hence assume that the evaluation of the innovation is unproblematic. By contrast, I have argued that decision makers have difficulty judging the value of innovations, making trusted information about the innovation necessary for adoption. Valuable innovations will spread slowly whenever there are firms that cannot easily observe which other firms have adopted the innovation and what their experience with it has been. Hence, when there is meaningful variation in the knowledge about a valuable innovation, proximity to innovators and adopters is a source of competitive advantage. This study has documented this claim by showing slow and selective diffusion of two innovative production assets that were readily available from their makers: the post-Panamax container ship and the double-hull oil tanker.

The evidence presented here has implications for the resource-based view, cluster theory, and network theory. The first implication is straightforward. The slow and selective diffusion of these two innovations shows that technological innovations can be a source of competitive advantage over a



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strategically significant time span. The advantage obtained by being an early adopter is cumulative because early adopters add to their advantage by making additional adoptions before many competitors have made their first adoption of the new technology. Hence, it becomes interesting to study how a firm can be positioned to become an early adopter of a technological innovation. Here, cluster theory and network theory make clear predictions, some of which are supported in the analysis.

For cluster theory, the local diffusion of post-Panamax ships (and double-hull tankers in Model 3) is evidence in favor of spatial clusters of firms adopting innovations that give competitive advantage, and thus support Porter (1990). This support is tempered by the broad spatial distribution of supplier-buyer networks and their effect on the diffusion of the two innovations. In order to retain competitive advantage in the local cluster, innovations should spread locally and should not spread broadly. The dispersion of these ship types could be a problem for the less connected firms in clusters, because when an innovation consequential for competitive advantage spreads to some members outside the local cluster and not to all members inside, their competitive advantage is weakened. The diffusion of the post-Panamax container ship and the double-hull tanker suggests that the advantage of a spatial clusters location is not realized by all firms in clusters and is matched by an advantageous network position for some firms outside clusters. The network effect is not a simple cohesion effect of sharing the same technology supplier, but is instead associated with network positions that allow comparison of information from multiple sources. Hence, a revised cluster theory that takes supplier-buyer networks into account should also incorporate ideas from network theory.

For network theory, the analysis showed that the affiliation network between shipbuilders and shipping firms affected the diffusion of innovations. Firms with a central location in the network (for tankers only) and firms in the same network cluster as prior adopters were likely to adopt, as one would expect if information transmitted via network ties helped managers learn about the innovation and judge its value with confidence. In spite of the many prior studies of diffusion, these findings are novel, because they are from a context in which firms have strong incentives not to spread accurate information about the innovation. It seems likely that the shipbuilders used adoptions by other firms as references in their marketing of innovative ship types, and that this information was viewed as most trustworthy by firms having many network ties and firms sharing shipbuilders with prior adopters. It is unlikely that much direct contact took place between early and late adopters given that each adopter would have had an interest in concealing the advantage of adopting in order not to help competitors. A case in point is that when Maersk ordered the *Emma Maersk*, now the largest container ship in the world and the first of a series of 10, it did not immediately announce the capacity. Shortly before the launch, Maersk did issue a press release stating the capacity, but used an idiosyncratic measure that understates the capacity relative to the usual measures. However, these attempts of secrecy were undermined by news services, which offered early size estimates and recalculated the size by conventional standards when reporting Maersk's press release.[4]

The findings indicate a need to revise the theory of competitive advantage to take into account the effect of selective diffusion of supplier innovations through interorganizational networks. In these data, Porter's (1990) claims about the effect of suppliers of production equipment on the competitiveness of the users were correct when moved from the spatial-cluster to the network-cluster level of analysis. However, the assumption that the spatial and network clusters would overlap proved not to hold. Clearly, the network cohesiveness of spatial clusters should become a much more prominent issue in the theory of spatial clusters (Lazerson and Lorenzoni, 1999; McEvily and Zaheer, 1999; Breschi and Lissoni, 2001). Considering network clusters is not a problem-free modification of the theory, however, because it raises the question of what to do when different networks—producer, supplier, and customer—have different structures. Does competitive advantage require the same cluster of firms to appear at the nexus of all these networks, or is it enough that it appears in one network? If one is enough, which network is most important?

These findings suggest that network position is a source of competitive advantage, as some

[4] Maersk gives the capacity as 11,000 TEU. Prerelease estimates were over 10,000 and perhaps as much as 15,000. Lloyds Fairplay gives the capacity as 12,500-13,500 TEU depending on the type of container used. The difference is that the Maersk capacity measure assumes that the ship cannot fill all its container slots.



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have already argued (Owen-Smith and Powell, 2004; Lavie, 2006). However, network sources of competitive knowledge are not only found through access to bits of external knowledge that need to be assembled internally in order to become products, as in the studies on network effects on innovativeness, they are also found in the far simpler context of ready-made innovations that are for sale. Once network position and cluster are seen as sources of competitive advantage, some difficult questions follow. Is it necessary to also consider the competitive advantage of groups of firms, as when multiple firms are located so that they have early access to innovations? Should the theory on the resources that give competitive advantage be revised so that the criterion is no longer just characteristics of the resource (e.g., tacitness), but also of the industry social network?

## CONCLUSION

Management theory is sometimes criticized for containing many theoretical perspectives with little interaction and insufficient examination of assumptions and evidence (Pfeffer, 1993), as opposed to the fish-scale model of science in which perspectives are partially overlapping and inform each other (Campbell, 1969). There is work that combines and compares different theoretical perspectives, however, and these studies can be highly informative of their theoretical development and empirical fit (e.g., Palmer *et al*., 1993; Uzzi, 1997; Zajac and Westphal, 2004). Still, such comparison occurs less often than it might, perhaps because the derived propositions most often tested tend to differ by theory, and thus it is easy to overlook that multiple theories can have predictions for a single outcome. Testing predictions on outcomes that are one step prior to the final outcome, such as when analyzing diffusion to evaluate theories of competitive advantage, can be a very strong lever for comparing theories because early steps in the causal chain have consequences for the following reasoning.

Here, the implications of cluster theory and network theory for the diffusion of production technology innovations were tested. It is not a coincidence that these theories had different implications for diffusion. Theory about competitive advantage requires a view on how information spreads and is acted on, and this is such a classic and contested theoretical question that there is a smorgasbord of assumptions to choose from. Theorists seeking clean conclusions prefer a simple assumption, but empirical work finds that multiple mechanisms are in play when innovations spread (Karshenas and Stoneman, 1993; Davis and Greve, 1997). Studying different theoretical mechanisms jointly gives better understanding of the phenomena and can suggest theoretical reformulations through integrating the best-supported parts of each theory and discarding unsupported parts.

This investigation showed an important link between diffusion theory and the theory of competitive advantage. Because uncertainty about the value of innovations results in slow and selective diffusion, they remain rare long enough to give early adopters competitive advantage. This feature of diffusion processes suggests that imperfect imitability is obtained more easily than strict versions of the resource-based theory assume. Uncertainty is a weaker condition than tacit knowledge, but is sufficient to produce slow diffusion. As evidence for this suggestion, this study showed that two supplier innovations spread slowly and selectively to the firms that had best access to information about them. The surprising conclusion is that there may be more sources of competitive advantage than theorists have assumed, because resources that in principle are obtainable by all will, in fact, be obtained by few firms only. Investigation of the speed and selectivity of innovation diffusion will be a valuable addition to the field of strategy.

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