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On the role of demand and strategic uncertainty in capacity investment and disinvestment dynamics

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ABSTRACT

Even mature industries seldom settle down into a long-run steady state. Fluctuations in demand disrupt the status quo and call for firms to adjust their capacities on an ongoing basis. We construct a fully dynamic model of an oligopolistic industry with lumpy capacity and lumpy investment/disinvestment decisions. In addition to uncertainty about the evolution of demand, a firm faces strategic uncertainty concerning the decisions of its rivals. We numerically solve the model for its Markov-perfect equilibria. For one set of parameter values, three equilibria exist, and while all of them have simple, intuitive structures, they exhibit widely varying patterns of response to demand shocks. At one extreme, one firm dominates the industry almost as a monopolist and changes its capacity to accommodate demand. At the other extreme, the larger firm keeps its capacity nearly constant while the smaller firm acts as the swing producer.

1. Introduction

In oligopolistic industries firms face at least two types of uncertainty. First, there is uncertainty about the evolution of demand and possibly also production technology. This type of uncertainty is typically exogenous to the industry. Second, there is uncertainty that emerges endogenously from the strategic decisions of firms. This strategic uncertainty often arises because a firm does not know the exact cost structure of its rivals and therefore cannot perfectly predict their decisions. It matters because a firm's decision regarding capacity addition and withdrawal has both an immediate impact on the profitability of its rivals and the potential to shape the evolution of the industry for years to come.

In practice demand uncertainty and strategic uncertainty are important, and the strategic management literature on capacity decisions exhorts managers to think carefully about both. For example, in his classic work *Competitive Strategy*, Michael Porter writes: “Because capacity additions can involve lead times measured in years and capacity is often long lasting, capacity decisions require the firm to commit resources based on expectations about conditions far into the future. Two types of expectations are crucial: those about future demand and those about competitors' behavior. The importance of the former in capacity decisions is obvious. Accurate expectations about competitors' behavior is essential as well, because if too many competitors add capacity, no firm is likely to escape the adverse consequences” (Porter, 1980, p. 324). Highlighting how strategic uncertainty can complicate the formation of expectations about competitors' behavior, Porter goes on to state, “If firms have differing perceptions of each other's relative strengths, resources, and staying power, they tend to destabilize the capacity expansion process” (pp. 332–333).

Demand uncertainty has received much attention in the literature, and there is by now a large body of research about investment under this type of uncertainty (see Dixit and Pindyck, 1994). This real options theory mainly considers monopolistic or perfectly competitive settings. There are but a few papers combining real options theory with the strategic interactions that arise in dynamic games played by multiple firms. Most study simple games that end once the option has been exercised (e.g., Smets, 1991; Grenadier, 1996; Lambert and

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Perraudin, 2003; Boyer et al., 2004; Huisman and Kort, 2004; Pawlina and Kort, 2006; Mason and Weeds, forthcoming). Examples include adopting a new technology or entering a new market.[1] It is not possible to partially recover the investment or to follow up on it with additional investments.

In Besanko et al. (forthcoming) we consider a setting that is flexible enough to characterize fully or partially sunk investment. Our model of an oligopolistic industry is fully dynamic in that a firm can in each period decide to add or withdraw capacity. While we abstract from demand uncertainty, we capture the strategic uncertainty that firms face about their rivals' investment/disinvestment decisions by assuming that a firm is privately informed about its own cost/benefit of capacity addition/withdrawal. We show that, under certain conditions, the evolution of the industry takes the form of a race. Each firm invests aggressively to expand its capacity before its rivals can do so. The industry ultimately reaches an asymmetric structure dominated by the winner of the race. Pursuing an aggressive approach to investment in an attempt to preempt rivals is thus a deliberate competitive move that has a lasting effect on the structure of the industry. This is consistent with the dominance of DuPont of the North American titanium dioxide industry that can be traced back to the preemptive strategy of capacity accumulation that DuPont initiated in the early 1970's (Ghemawat, 1984; Ghemawat, 1997; Hall, 1990). Indeed, in 2008, more than thirty-five years after launching its strategy of capacity preemption, DuPont's share of capacity in the U.S titanium dioxide market is over 50 percent (the next largest competitor Tronox has 20 percent), and DuPont's 21 percent global market share makes it the largest titanium dioxide seller in the world.

In this paper, we build on Besanko et al. (forthcoming) to explore capacity investment and disinvestment dynamics under both demand and strategic uncertainty. Without demand uncertainty, the case studied by Besanko et al. (forthcoming), the role of strategic uncertainty is bound to diminish over time: Once the industry has reached a "steady state," investment activity comes to a halt, except possibly to make up for depreciation. Hence, it may not matter much that a firm does not know the exact cost structure of its rivals and therefore cannot perfectly predict their decisions to add or withdraw capacity. Fluctuations in demand call for firms to adjust their capacities on an ongoing basis and therefore ensure the continued importance of strategic uncertainty. Moreover, a sufficiently large swing in demand may upset the established structure of the industry. Combing the two types of uncertainty in one model allows us to answer questions regarding the identity of the swing producer and whether a firm is able to maintain—or perhaps even improve—its competitive position in the face of demand uncertainty.

2. Model

We incorporate demand uncertainty into the fully dynamic model of an oligopolistic industry with lumpy capacity and lumpy investment/disinvestment developed and analyzed in Besanko et al. (forthcoming). The description of the model is abridged; we refer the reader to Besanko et al. (forthcoming) for details. The state of demand d takes on one of D values, 1, 2, …, D. There are two firms, indexed by 1 and 2, with potentially different capacities $\overline{q}_i$ and $\overline{q}_j$, respectively. Capacity is lumpy so that $\overline{q}_i$ and $\overline{q}_j$ take on one of M values, 0, Δ, 2Δ, …, $(M-1)\Delta$, where $\Delta>0$ measures the lumpiness of capacity. We refer to $(d,i,j)\in\{1,2,\ldots,D\}\times\{0,1,2,\ldots,(M-1)\}^2$ as the state of the industry; in state (d,i,j) the state of demand is d and firm 1 has a capacity $\overline{q}_i$ of $i\Delta$ units and firm 2 has a capacity $\overline{q}_j$ of $j\Delta$ units.

Time is discrete and the horizon is infinite. At the beginning of a period, firms first learn their cost/benefit of capacity addition/withdrawal. To firm 1 the cost of adding Δ units of capacity is $\eta_{e,1}=\phi_e+\varepsilon_e\theta_1$ and the benefit of withdrawing Δ units is $\eta_{w,1}=\phi_w+\varepsilon_w\theta_1$, where θ_1 is a mean-zero random variable with support $[-1, 1]$, and ϕ_e, ϕ_w, $\varepsilon_e>0$, and $\varepsilon_w>0$ are location and scale parameters, respectively. The difference between the expected cost of capacity addition ϕ_e and the expected cost of capacity withdrawal ϕ_w is a measure of the expected sunkness of investment. To capture the changing nature of investment opportunities, we assume that θ_1 is drawn anew each period and that draws are independent across periods and firms. Its cost/benefit of capacity addition/withdrawal is private to a firm and hence unknown to its rival. Incorporating incomplete information in this way allows us to capture the strategic uncertainty that firms face about their rivals' investment/disinvestment decisions. Increasing the scale parameters ε_e and ε_w increases this uncertainty by giving a firm an incentive to time its investment and disinvestment decisions opportunistically so as to minimize the cost of capacity. Because θ_1 is private to firm 1, firm 2 as it makes its investment/disinvestment decisions in state (d, i, j) "sees" only the investment/disinvestment probabilities of firm 1,

$$e_1(d,i,j) = \int e_1(d,i,j,\theta_1)dF(\theta_1),\ w_1(d,i,j) = \int w_1(d,i,j,\theta_1)dF(\theta_1),$$

rather than its decisions $e_1(d, i, j, \theta_1)\in\{0, 1\}$ and $w_1(d, i, j, \theta_1)\in\{0, 1\}$ to add or withdraw Δ units of capacity.

After firms have made their investment/disinvestment decisions, but before these decisions are implemented, they compete in a differentiated product market by setting prices subject to capacity constraints. We assume soft capacity constraints in that capacity reduces a firm's marginal cost of production at any given level of output. In particular, firm 1's marginal cost is $MC(q_1,\overline{q}_i) = \left(\frac{q_1}{\overline{q}_i}\right)^\nu$, where $\nu>0$. The larger is ν the closer we are to hard capacity constraints because the marginal cost is close to 0 for $q_1<\overline{q}_i$ and rises rapidly for $q_1>\overline{q}_i$. In the computations described below, we use a relatively large value of ν to approximate hard capacity constraints. The Nash equilibrium of the product market game determines firms' single-period profit functions $\pi_1(d,i,j)$ and $\pi_2(d,i,j)$. In the product market game, the demand function for firm 1 is

$$q_1(p_1,p_2;d) = \frac{1}{1-\gamma^2}(a(1-\gamma)-b_dp_1 + \gamma b_dp_2),$$

where $\gamma\in[0, 1)$ measures the degree of product differentiation (0 for independent goods and 1 for perfect substitutes). Depending on the state of demand d, the slope b_d of this demand function takes on one of the D values, i.e., $b_d\in\{1.5b, 1.25b, b, 0.75b, 0.5b\}$, where $b_d=b$ is the baseline level of demand, $b_d>b$ is a contraction of demand, and $b_d<b$ an expansion. Specifically, the aggregate demand function is $Q(P;d) = \frac{2}{1+\gamma}(a-b_dP)$, where $P = \frac{1}{2}(p_1+p_2)$, with inverse $P(Q;d) = \frac{1}{b_d}\left(a-\frac{1+\gamma}{2}Q\right)$. A change in b_d causes the inverse demand function to rotate about its horizontal intercept. Such a rotation makes invariant, at any given quantity, the price elasticity of aggregate demand. Therefore, consumers willingness to pay for any given quantity is two thirds of its baseline level in the worst demand state $d=1$ and double its baseline level in the best demand state $d=5$.[2] The state of demand follows an exogenous Markov process. From one period to the next, d goes up or down with equal probability $\rho\in(0, 0.5]$.[3] If $\rho=0$, then the state of demand never changes, and it surely changes if $\rho=0.5$; hence, ρ is a measure of demand uncertainty. Because the probabilities of going up and down are equal, the limiting (ergodic) distribution over demand states is uniform and the

[1] Indeed, strategic real options theory can be traced back to Fudenberg and Tirole's (1985) work on preemption in the adoption of a new technology.

[2] An increase in demand for a firm is an outward shift of its demand curve. Three polar cases are rotation around the horizontal intercept, rotation around the vertical intercept, and parallel shift.

[3] If demand is in the lowest (highest) state, then we assume that it goes up (down) with probability ρ.

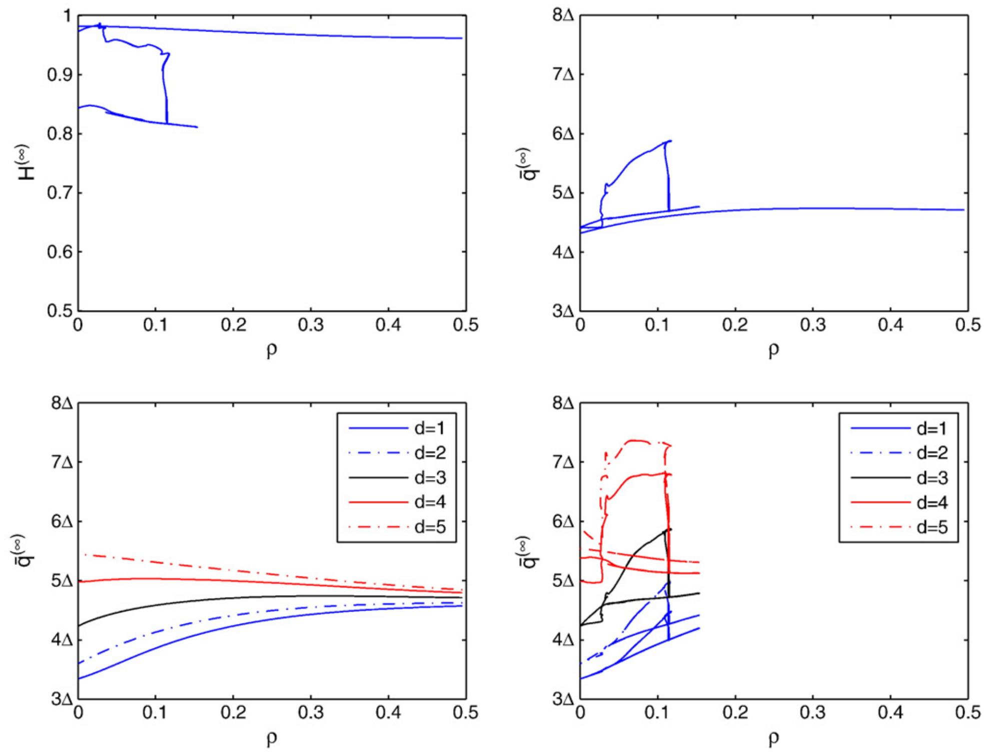

Fig. 1. Herfindahl index of firms' capacities $H^{(\infty)}$ (top left panel) and total capacity $\bar{q}^{(\infty)}$ unconditional (top right panel) and conditional on the state of demand (bottom panels).

expectation of b_d is equal to b so that $b_d = b$ is indeed the baseline level of demand.

At the end of the period, the investment/disinvestment decisions are implemented and previously installed capacity is subjected to depreciation. We think of depreciation as being of a physical nature such as machine breakdowns, technological obsolescence, and natural disasters, and assume that a firm is subjected to depreciation with probability $\delta \in [0, 1]$. The state of demand finally changes according to the exogenous Markov process specified above. Hence, the industry transits from its current state (d, i, j) to some other state (d', i', j') at the beginning of the subsequent period.

The solution concept is symmetric Markov-perfect equilibrium (MPE). Existence follows from the arguments in Doraszelski and Satterthwaite (2010). Below we focus on the case of almost perfect substitutes ($\gamma = 0.99$), partially sunk investment ($\phi_e = 72$ and $\phi_w = 24$), and significant depreciation ($\delta = 0.1$). We set the stage for strategic uncertainty by assuming substantial variation in the cost/benefit of capacity addition/withdrawal across firms and periods ($\varepsilon_e = 36$ and $\varepsilon_w = 12$). The remaining parameter values are as described in Besanko et al. (forthcoming). We use the homotopy path-following method, first applied to dynamic stochastic games by Besanko et al. (2010) (see also Borkovsky et al., forthcoming), to map out the equilibrium correspondence of our game; we are particularly interested in how equilibrium behavior and the industry dynamics implied by it change with ρ, our measure of demand uncertainty.

3. Results

In Besanko et al. (forthcoming) we study the special case without demand uncertainty ($D = 1$ or $\rho = 0$). We show that low product differentiation, low investment sunkness, and high depreciation promote preemption races. During a preemption race, firms continue investing as long as their capacities are similar. The race comes to an end once one of the firms gains the upper hand. At this point, the investment process stops and a process of disinvestment starts. During the disinvestment process some of the excess capacity that has been built up during the race is removed.[4]

Low product differentiation intensifies capacity utilization and price competition and incentivizes both the leader and the follower to start the disinvestment process at the end of a preemption race in order to restore the industry to profitability. Both low investment sunkness and high depreciation imply high investment reversibility and promote preemption races by allowing firms to remove some of the excess capacity that has been built up during the race. In contrast, if they lack a means to remove capacity, then firms have no reason to enter a preemption race in the first place because they anticipate that the industry will be permanently locked into a state of excess capacity and low profitability after the race.[5]

While the idea that reversibility can spur rather than hinder preemption contrasts with conventional wisdom in investment theory (see, e.g., p. 345 of Tirole, 1988), it is in line with the empirical findings in the North American newsprint and U.K. brick industries. These industries differ mainly in the sunkness of investment. In the former, investment sunkness is low and there is evidence suggestive of "some sort of race to add capacity" (Christensen and Caves, 1997, p. 48). In the latter, in contrast, investment sunkness is high and "in general brick firms manage to sequence successfully their capacity expansion insofar as they avoid excessive contemporaneous bunching of expansions" (Wood, 2005, p. 43).

[4] The "war-of-attrition entry" that Cabral (2004) considers is analogous to the preemption races that arise in our model. His model, however, has no disinvestment so capacity coordination cannot occur in the long run.

[5] Besanko and Doraszelski (2004) have previously made the point that high reversibility in the form of significant depreciation can spur preemption races. In Besanko et al. (forthcoming) we show that depreciation—the involuntary withdrawal of capacity—and disinvestment—the voluntary withdrawal of capacity—are less than perfect substitutes. In particular, although depreciation removes capacity, it may impede capacity coordination. The reason is that depreciation is beyond the control of firms. Hence, the leader keeps a "safety stock" of capacity to counter the risk that the industry leadership is lost to depreciation. This hinders capacity coordination.

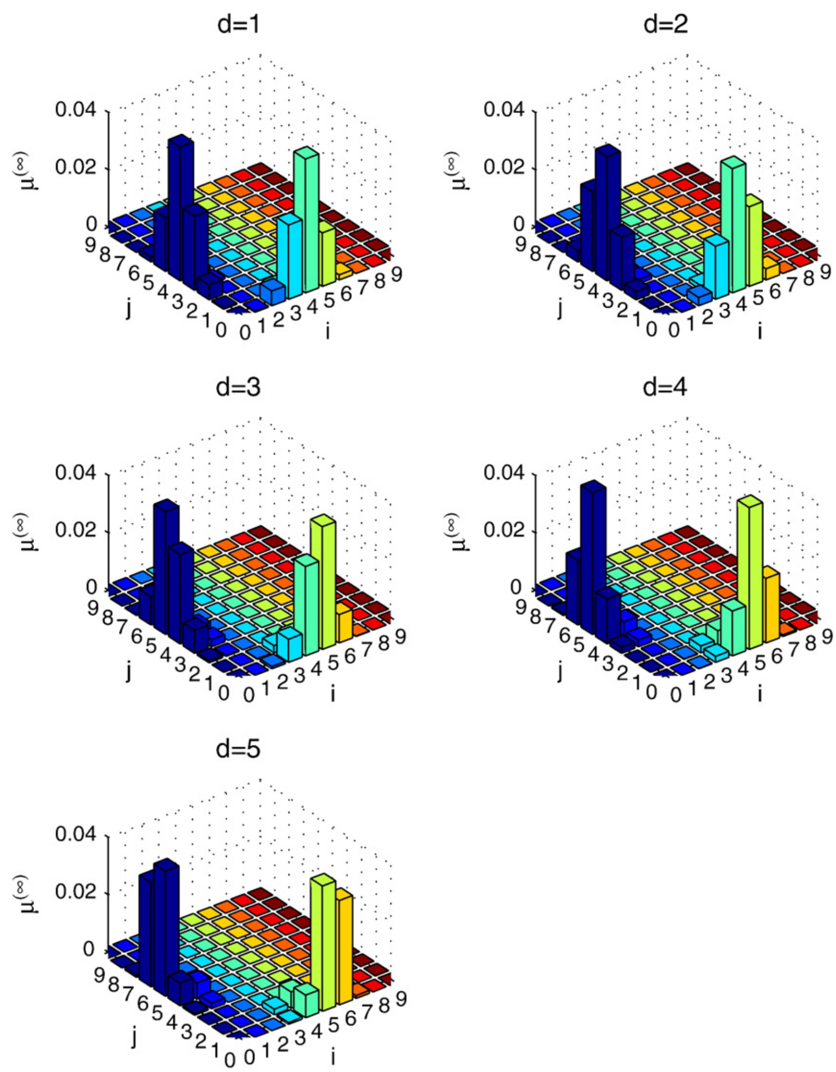

Fig. 2. Limiting distribution $\mu^{(\infty)}$. First equilibrium.

We also show that low product differentiation and low investment sunkness promote capacity coordination in the sense that in the long run there is little (if any) excess capacity relative to the benchmark of a capacity cartel. Therefore, preemption races and excess capacity in the short run often go hand-in-hand with capacity coordination in the long run. The association of these seemingly contradictory behaviors is consistent with observing both preemption races and capacity coordination in the North American newsprint industry where investment is partially sunk. It is also consistent with Gilbert and Lieberman's (1987) finding that in the 24 chemical processing industries studied preemption may be a temporary phenomenon and that “the main role of preemptive activity is to coordinate new investment and to promote efficiency by avoiding excess capacity” (p. 30).

In the remainder of this paper, we consider the model with demand uncertainty ($D>1$ and $\rho>0$). We ask how demand uncertainty affects equilibrium behavior and the industry dynamics implied by it. Having computed an equilibrium for a particular parameterization of the model, we use the investment/disinvestment probabilities $e_1(d,i,j)$ and $w_1(d,i,j)$ along with the exogenous Markov process governing demand to construct the probability distribution over next period's state (d', i', j') given this period's state (d, i, j). With this transition matrix in hand, we are able to characterize equilibrium industry dynamics by computing the distribution over states, and hence the structure of the industry, at any point in time. The limiting distribution $\mu^{(\infty)}$ over states describes the industry in the long run.[6] From it, we compute the Herfindahl index of firms' capacities as

$$H^{(\infty)} = \sum_{d=1}^{D}\sum_{i=0}^{M-1}\sum_{j=0}^{M-1}\left(\left(\frac{\bar{q}_i}{\bar{q}_i + \bar{q}_j}\right)^2 + \left(\frac{\bar{q}_j}{\bar{q}_i + \bar{q}_j}\right)^2\right)\mu^{(\infty)}(d,i,j).$$

The Herfindahl index summarizes expected industry structure and dynamics. To the extent that it exceeds 0.5, an asymmetric industry structure arises and persists in the long run. We additionally compute the total capacity of the industry implied by the equilibrium in the long run as

$$\bar{q}^{(\infty)} = \sum_{d=1}^{D}\sum_{i=0}^{M-1}\sum_{j=0}^{M-1}\left(\bar{q}_i + \bar{q}_j\right)\mu^{(\infty)}(d,i,j).$$

We finally compute the total capacity of the industry conditional on the state of demand.

Fig. 1 visualizes the equilibrium correspondence for a range of values for ρ, our measure of demand uncertainty. The top left panel

[6] Let P be the $DM^2 \times DM^2$ transition matrix of the Markov process of industry dynamics. The limiting distribution over states solves $\mu^{(\infty)} = \mu^{(\infty)}P$.

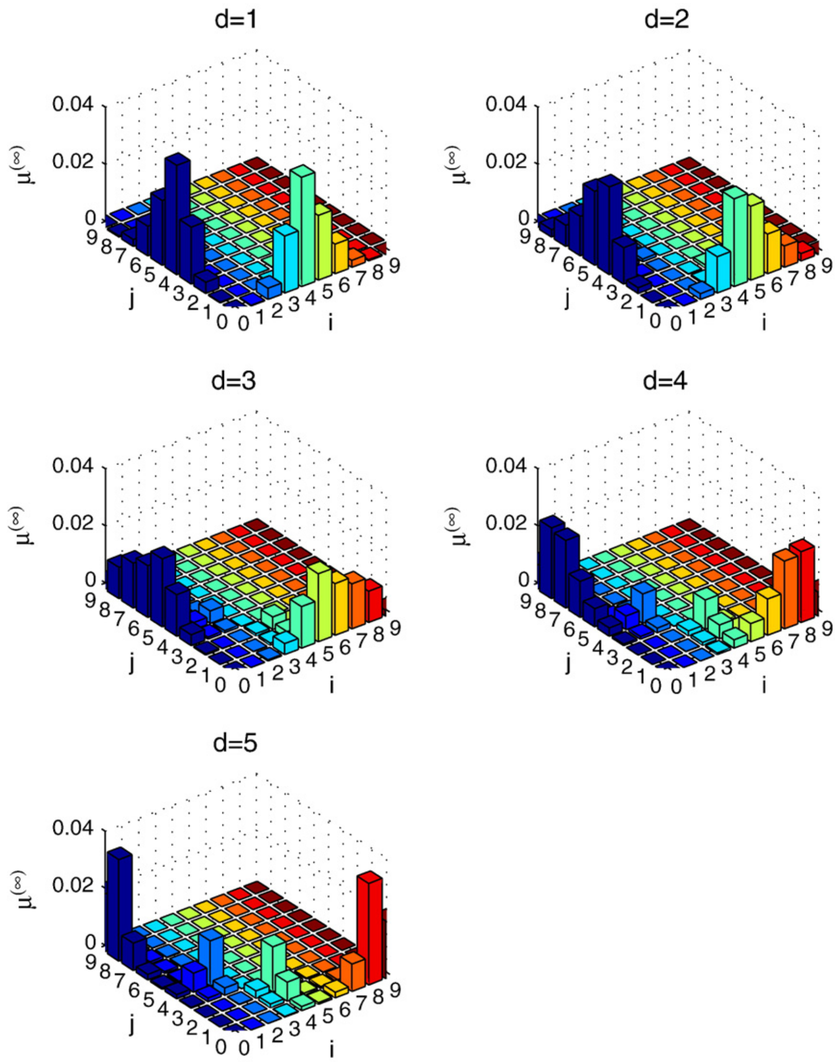

Fig. 3. Limiting distribution $\mu^{(\infty)}$. Second equilibrium.

depicts the Herfindahl index, the remaining panels the total capacity of the industry first unconditional and then conditional on the state of demand. As can be seen in the top left panel, the equilibrium correspondence consists of a main path that starts at $\rho=0$ and ends at $\rho=0.5$. In addition, there is a path that forms an arc starting at $\rho=0$ and ending at $\rho=0$. Consequently, for values of ρ below 0.15, there are multiple equilibria. As demand uncertainty increases further, we have found just one equilibrium.[7]

The Herfindahl index in the top left panel of Fig. 1 and the total capacity of the industry in the top right panel both change little with demand uncertainty. The Herfindahl index indicates that the industry is typically highly concentrated. The bottom panels depict the total capacity of the industry conditional on the state of demand. For clarity the bottom left panel corresponds to the main path of equilibria and the bottom right panel to the arc. The total capacity of the industry changes with the state of demand. However, the differences generally diminish with demand uncertainty. This is intuitive because as fluctuations in demand from period to period become more likely, firms are better off to build capacity to cater to average demand and avoid costly adjustments to their capacities. That firms act cautiously under demand uncertainty has been demonstrated both theoretically and empirically. A recent paper by Bloom et al. (2007) shows that with partial irreversibility, increased demand uncertainty decreases the responsiveness of investment to fluctuations. Similar to this, in our model firms become increasingly cautious in their investment and disinvestment behavior, but they do so in the context of oligopolistic competition rather than a single-agent decision problem.

We next take a closer look at the differences between the multiple equilibria that arise for a particular degree of demand uncertainty. As can be seen in Fig. 1, the three equilibria for $\rho=0.1$ differ in terms of the Herfindahl index ($H^{(\infty)}=0.98$, 0.95, and 0.82) and the total capacity of the industry ($\overline{q}^{(\infty)}=4.58$, 5.78, and 4.67).[8] Even more interesting, the three equilibria exhibit very different patterns of how the individual firms respond to fluctuations in demand. To illustrate, we depict in Figs. 2–4 the limiting distribution over states.

The first equilibrium gives the most asymmetric long-run industry structure and the lowest total capacity. As can be seen in Fig. 2, the industry is most likely dominated by a large firm with 4Δ or 5Δ units of capacity while the small firm has 0Δ units. As our model assumes

[7] These are the equilibria we have found; there may be others we have not identified.

[8] Notice that the arc in the top right panel of Fig. 1 is inverted relative the one in the top left panel, which explains that the equilibrium with the second highest $H^{(\infty)}=0.95$ has the highest $\overline{q}^{(\infty)}=5.78$.

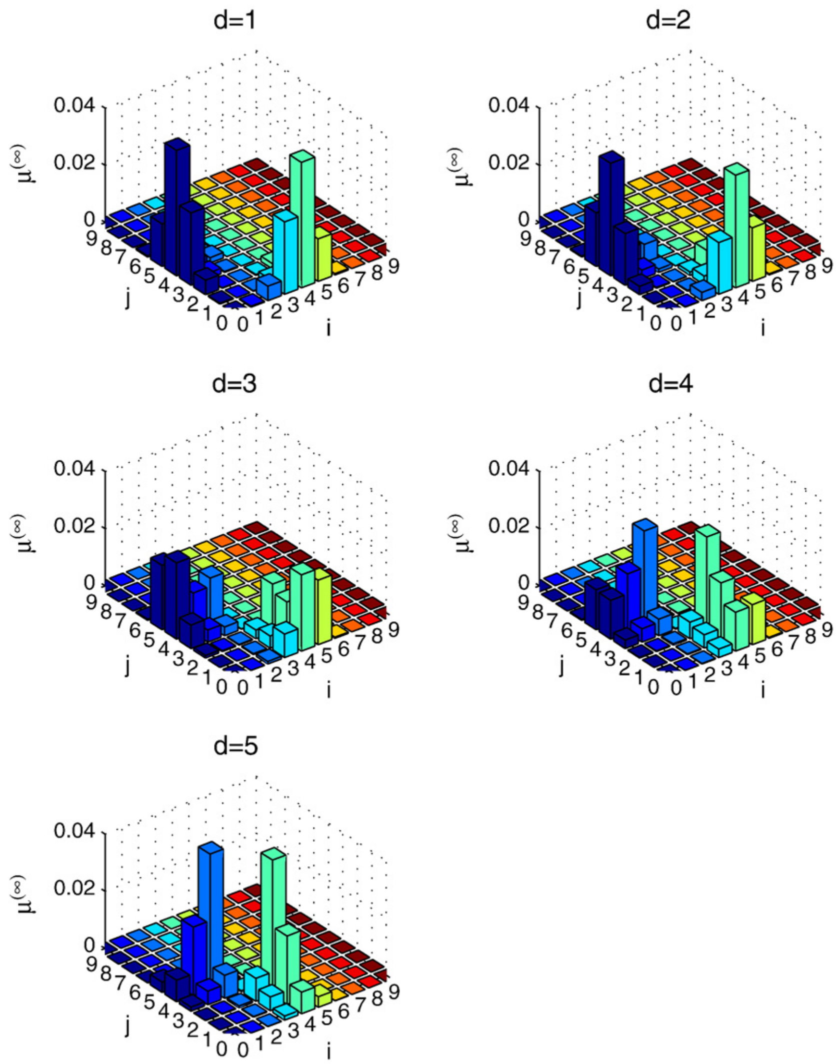

Fig. 4. Limiting distribution $\mu^{(\infty)}$. Third equilibrium.

that a firm with zero capacity faces zero demand, the large firm is in effect a monopolist. Moreover, the small firm has very little chance to "break into" the market: even when demand conditions are most favorable ($d=5$, bottom left panel), the small firm is still most likely to have 0Δ units of capacity. The large firm also does little to adjust to fluctuations in demand. It is most likely to have 4Δ units of capacity in the worst demand state ($d=1$, top left panel) compared to 5Δ units in the best demand state ($d=5$, bottom left panel).

As a consequence, in the first equilibrium the total capacity increases in expectation from 3.86Δ units in the worst demand state to 5.31Δ units in the best demand state. In contrast, in the second equilibrium, the total capacity of the industry is much more responsive to fluctuations in demand: it increases in expectation from 4.26Δ units in the worst demand state to 7.32Δ units in the best demand state (see bottom panels of Fig. 1). Hence, in the second equilibrium the total capacity of the industry adjusts to meet demand, a phenomenon observed by Booth et al. (1991) in their study of the highly cyclical North American newsprint industry.

In the second equilibrium, in the worst demand state, the industry is almost certainly dominated by a large firm, most likely with 4Δ units of capacity while the small firm has 0Δ units (see top left panel of Fig. 3). In the best demand state, the industry is still most likely to be dominated by a large firm, now with 8Δ units of capacity while the small firm has 0Δ units (see bottom left panel). Thus for most sequences of private shocks to the cost/benefit of capacity addition/withdrawal, the large firm acts as the swing producer that adjusts to fluctuations in demand. Indeed, the leader defends its dominant position by aggressively investing in up to 8Δ units of capacity, leaving the follower little room for survival. But for some sequences of private shocks the roles reverse. As can be seen in the bottom left panel of Fig. 3, in the best demand state, there is a good chance that the industry reaches either state (4, 2) or state (2, 4). Now the follower is the swing producer and uses "good times" as an opportunity to enter the market and partially catch up with the leader.

The third equilibrium gives the least asymmetric long-run industry structure. The total capacity of the industry increases in expectation from 3.93Δ units in the worst demand state to 5.36Δ units in the best demand state, quite comparable to the first equilibrium (see bottom panels of Fig. 1). As can be seen in Fig. 4, however, the leader behaves much softer and, in good times, allows the follower to break into the market. Indeed, the large firm is most likely to remain at 4Δ units of capacity irrespective of the state of demand. The small firm is always the swing producer.

Our findings on how the individual firms respond to fluctuations in demand are not easily explained by the existing literature. Ghemawat and Nalebuff (1985) show that, in a deterministically declining market, the larger (higher-capacity) firm exits first.[9] Ghemawat and

[9] Fudenberg & Tirole (1986) show that the higher-cost firm exits first.

Nalebuff (1990) assume that firms can continuously adjust their capacities (rather than exit) and show that, again, the larger firm shrinks first. Once it has reached the same size as its rival, both firms continue shrinking together. Whinston (1988) shows that anything can happen if firms have multiple plants; in particular the larger firm (with two plants) does not necessarily exit before the smaller firm (with one plant). What happens depends on the details of the model, and there are no simple rules. However, if firms differ only in the number of plants that they own and plants are identical, a scenario that seems close to our model, then the larger firm is necessarily the swing producer (Whinston 1988, pp. 584–585).

In contrast, our results show that the swing producer can be either the large firm or the small firm depending on the equilibrium the industry settles on. Since there are multiple equilibria, the economic primitives do not suffice to tie down firms' behavior. How the industry evolves depends on how firms expect the industry to evolve.

In sum, our model of capacity investment and disinvestment dynamics under both demand and strategic uncertainty generates new and interesting insights. Our examples show that demand uncertainty can have an impact on the multiplicity of equilibria. Further, as demand becomes more uncertain, firms become more hesitant to adjust their capacities. Different equilibria exhibit different levels of aggressiveness in the follower's threatening expansion and the leader's defensive expansion in response to fluctuations in demand. The swing producer can be either the large firm or the small firm, and sometimes the identity of the swing producer may depend on firms' expectations regarding the future evolution of the industry. Whether any of these behaviors generalizes is an open question that we intend to pursue in future research.

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