Open versus Closed firms and the Dynamics of Industry Evolution [†]

Ashish Arora [a] and Farasat A.S. Bokhari [b,*]

[a] *H. John Heinz III School of Public Policy and Management, Carnegie Mellon University, PA 15213*

[b] *Department of Economics, Florida State University, FL 32306*

Last Revised: July, 2006

Abstract

We develop a model of industry evolution in which firms choose proprietary standards (closed firm) or adopt a common standard (open firm). A closed entrant can capture multiple profits whereas an open entrant faces lower entry barriers: The odds of closed entry (relative to open entry) decrease with price and eventually open entry becomes more likely. While initially closed firms have better survival because they can offset losses in one component with profits from another, the situation is reversed when prices fall below a threshold. These entry and exit dynamics can lead the industry away from its long run equilibrium.

Key words: Open firms, Closed Firms, Specialization, Vertical Integration, Industry Evolution, Transaction Costs, Simulation Models

Published:

Journal of Industrial Economics, 55(3), 499-527, 2007

[†] Earlier drafts of this paper were circulated with the working title, "Returns to Specialization, Transaction Costs, and the Dynamics of Industry Evolution". We have benefited greatly from detailed comments and advice from anonymous reviewers and Pierre Régibeau, the reviewing editor. We also thank Marty Gaynor, Steve Klepper, Richard Nelson and Lowell Taylor for helpful comments on an earlier draft. The usual disclaimers apply. Authors listed in alphabetical order.

[*] Corresponding author: Farasat Bokhari (fbokhari@fsu.edu)

Email addresses: ashish@andrew.cmu.edu (Ashish Arora), fbokhari@fsu.edu (Farasat A.S. Bokhari).

1. Introduction

Many products consist of more than one component. If these components are produced by distinct firms, these firms must agree upon standards and interfaces for the components. By contrast, if all components are under the control of a single firm, the firm need not use the common standard. Farrell, Monroe, and Saloner (1998) label these "open" and "closed" systems respectively, a terminology we adopt as well. A variety of industry patterns can be observed.

In enterprise software, for instance, SAP offers a closed product (an "integrated suite", to use the industry term), with various application modules designed to work with the basic SAP enterprise resource planning (ERP) platform. Instead, until recently, users could opt for an Oracle database platform, using applications from Peoplesoft for human resources, JD Edwards for financial management, Siebel for customer relationship management and so on. In the last couple of years, all of these companies were acquired by Oracle, and it is likely that in the future, it will offer an integrated suite as well, so that we might see only competing closed systems in this market. One can also find examples where the opposite trends are visible. For instance, the computer market was initially characterized by closed systems. In mainframes, IBM and companies like Burroughs provided complete closed systems. Like IBM, DEC built its strategy for minicomputers around a proprietary family of machines, with competitors such as Hewlett Packard and Wang following suit. In personal computers as well, Langlois (1992) shows that the early movers such as Apple, Commodore and Tandy offered machines that were substantially closed, especially as compared to the current situation where personal computers are composed of standard components that can be mixed and matched by assemblers such as Dell or Gateway.

One fundamental tradeoff underlying these conflicting trends is that open systems allow "mixing and matching" (Farrell and Saloner, 1985, 1986; Matutes and Regibeau, 1988; Economides, 1989) whereas closed systems reduce the costs of transacting across firm boundaries.[1] Instead of appealing to heterogeneity in preferences, we model the advantage of open systems by allowing firms to differ in their costs of producing various components. Since being a low cost producer of multiple components is more difficult, open systems have the advantage that firms can specialize in the production of single components. Closed firms, on the other hand, cannot. Our focus in this paper is to understand how this tradeoff affects the dynamics of an industry where both open and closed systems can compete.

To focus on this trade-off, we assume price taking firms with conventional U-shaped cost curves, thereby removing the complex strategic interactions that can arise when firms have market power.

[1]Related work has focused on the pricing of the product as a whole (or "bundling", as it is sometimes referred to) as compared to the prices of components (e.g., Matutes and Regibeau (1992) and, Denicolo (2000)). There is a much larger literature on bundling which we do not review here. See for instance, Adams and Yellen (1976), Schmalensee (1984) and Whinston (1990).

In our model, the long run equilibria are driven entirely by whether the costs of transacting across firm boundaries are outweighed by any diseconomies of scope.[2] Our focus, however, is on the short term dynamics; we show that the industry does not evolve monotonically to its steady state configuration. For example, we show that even when closed systems minimize long run costs, the industry may nonetheless move towards openness for sustained periods.

We model a product with two components. The industry consists of both open and closed firms. Customers treat both the open and the closed product as perfect substitutes, implying that product variety is not an issue. Given this, the only way being closed could be profitable is if this meant lower costs. We allow for this possibility but do not impose it. Instead, we restrict the open firms to produce only one component while closed firms produce both. Thus closed firms capture two profit margins whereas an open firm can capture only one. On the other hand, an open firm can enter by being efficient at producing only one component. By contrast, a closed firm must be "good enough" at producing both. In this sense, an open configuration allows for the market to "mix and match". This recalls an observation Charles Babbage made more than a century ago

> "... (T)he master manufacturer, by dividing the work to be executed into different processes, each requiring different degrees of skill or of force, can purchase exactly that precise quantity of both which is necessary for each process; *whereas, if the whole work were executed by one workman, that person must possess sufficient skill to perform the most difficult, and sufficient strength to execute the most laborious, of the operations into which the art is divided.*" (Babbage, 175-6 quoted in Rosenberg (1994) italics ours.)

We study the evolution of this trade-off between the "two profit margin" effect and the Babbage effect by using simulations from a simple two component industry where heterogeneous potential entrants choose to enter as either a closed or open firm. Firms that undertake all activities in-house are able to avoid the costs of transacting across firm boundaries but may face diseconomies of scope. By varying the relative magnitude of these two types of costs, we are able to explore both the cases where closed firms have a cost advantage over open firms or vice versa.

The simulations are followed from the time when the industry is young, with inefficient firms that have high production costs and prices, to the point where, due to entry and exits, the incumbent firms are almost maximally efficient and operating close to the minimum of the long run average cost curve. The simulations reveal some interesting patterns. First, there is a dynamic bias in favor of the open firms, i.e., even if there is no cost advantage to open firms, the entry and exit process leads to the industry being dominated by open firms. Second, in the early periods of the industry, the reverse is true, i.e., the closed configuration dominates. Overall then, our simulations show that typically the industry evolves such that it is dominated by closed firms in the early history and by

[2]In Farrell, Monroe, and Saloner (1998), open systems are more efficient, but also imply more severe price competition. With a large number of competitors, the increase in efficiency is outweighed by the increase in the "toughness of competition". In our model, firms are price takers and thus the "toughness of competition" effect is absent.

open firms in later periods. Third, there is path-dependence in the evolution and chance can set in motion an outcome that is different from the 'likely' outcomes reported above. For instance, in some individual simulations, where the industry starts with equal market share of open and closed firms, the industry comes to be dominated by closed firms early and then remains closed, never moving towards an open configuration.

What explains these patterns? There are two key elements of our story. The first is the Babbage effect - whereas a closed firm has to master an array of activities and processes, an open firm needs to master only a few. In our model, a potential entrant observes its capabilities before deciding whether to enter, and if so, whether it should produce one or both components. Thus, even though a firm would want to capture both profit margins, it is more likely to be able to master one production process rather than two. As prices fall, the "two profit margins" become less important than being good enough at producing both components. Thus, over the lifecycle of the industry, as prices fall, entry by open firms becomes relatively more likely. When a potential entrant can capture multiple profits, it enters as a closed firm, and operates at an "average" capability - where the average is over the capabilities in the two components. This, in turn, implies that entry and exit processes for closed firms are different: entry of a closed firm requires multiple "good" capabilities while the exit of a closed firm depends on the "average" capability of the firm. We show that parallel to entry, as prices fall, closed firms are also more likely to exit than comparable open firms.

The second element of our story is that the payoff to open firms depends on the efficiency and size of the sector supplying complementary products. This effect - the complementarity effect - is important when the size and efficiency of the two complementary sectors are unequal. While open entry always improves the relative odds of entry by a complementary firm (relative to entry by a firm of its own type or a closed standards firm), this advantage is transitory and short lived if the open sectors are of same size and efficiency since an actual entry by a complementary firm in the next period will reverse the relative odds. However, if the difference in the sectors is large, the complementary effect persists in the sense that the probability of entering as a closed firm is lower if the two open sectors are unequal compared to when the open sectors are of equal size and efficiency.

The analysis outlined above relies on two assumptions. First, that all open firms adopt the same standard and second, that the open firms cannot produce both components, while closed firms produce both. The first assumption is easily justified since, in our model, there is no incentive for more than one open standard to emerge. Even if there were more than one open standard, all open firms would choose the same standard.

The second assumption is more artificial. Though it is natural to assume that a closed firm will produce both components, the reverse is not necessarily true. A firm could choose to produce both components, albeit to an open standard. In our model, we have no exogenous source of advantage for closed firms, having ruled out product differentiation and having assumed firms to be price takers. We also do not assume that the transaction costs involved in combining products from different firms are always greater than possible diseconomies of scope. Instead, we allow for both possibilities. Thus we need something to make a closed configuration potentially attractive. We make this assumption, therefore, as a modeling device. Since our results show that the dynamics of industry evolution favor an open configuration, relaxing this assumption would only accentuate our results. We discuss this further in subsection 5.3 below. The rest of the paper is organized as follows.

The next section presents the model. Section III provides the results of the simulations and summarizes the main lessons of the simulations. Section IV explains the dynamics of the model. This is followed by a section on robustness and conclusions.

2. The Model

We model a competitive market with both closed and open firms. We assume that the final product consists of one unit each of two components, H and S. A firm can be closed, in which case it integrates the production of both components in-house, or it may be open and can specialize in the production of either of the two components. We assume that closed firms are integrated and do not buy from or sell to other firms due to design incompatibilities. Additionally, we restrict open firms to produce only one component (H or S). Thus, H-type firms buy component S from S-type firms at price p_s and compete in the final good market with closed firms, where the market price is p_q. The demand for the final product is given by

$$D(p_q) = a + bp_q. \tag{1}$$

Costs are assumed to be quadratic in output so that, using subscripts s, h and i to refer to S-type, H-type and I-type (closed) firms respectively, we write the cost function as

$$C_s(q_s, \theta_s) = \alpha + (q_s^2 + q_s)\theta_s + \tau \tag{2a}$$

$$C_h(q_h, \theta_h, p_s) = \beta + (q_h^2 + q_h)\theta_h + q_h p_s + \tau \tag{2b}$$

where α and β are the fixed costs, q_s and q_h are the outputs, θ_s and θ_h are the (in)efficiency parameters, and τ represents the transaction costs due to specialization. We assume that θ_s and θ_h are iid random variables, distributed uniformly over $[1, 2]$, that each firm draws upon entry into the industry, but after entry, are fixed for the life of the firm. The cost function for a closed firm with efficiency parameters θ_s and θ_h is simply the sum of the costs of producing S and H plus a diseconomies of scope parameter γ, minus the transaction costs 2τ. Using [2] and the requirement that the closed firm produces equal amounts of S and H, a closed firm's cost function can be written as

$$\begin{aligned} C_i(q_i, \theta_h, \theta_s) &= C_h(\cdot) + C_s(\cdot) - q_i p_s - (2\tau - \gamma) \\ &= \alpha + \beta + (q_i^2 + q_i)\theta_i + \gamma \end{aligned} \tag{3}$$

where $\theta_i = \theta_h + \theta_s$.

2.1. **Market Behavior.** Firms are price takers, and set output by equating marginal cost to the market price. This gives

$$q_i = (1/2)\Big(\frac{p_q}{\theta_i} - 1\Big) \tag{4a}$$

$$q_h = (1/2)\Big(\frac{p_q - p_s}{\theta_h} - 1\Big) \tag{4b}$$

$$q_s = (1/2)\Big(\frac{p_s}{\theta_s} - 1\Big). \tag{4c}$$

Prices are determined by the market clearing conditions

$$\sum_i^n q_i + \sum_h^m q_h = a + bp_q \tag{5a}$$

$$\sum_h^m q_h = \sum_s^k q_s \tag{5b}$$

where n, m and k are the number of I-type, H-type and S-type firms respectively at any given time (we suppress all time subscripts for convenience of exposition). Since transaction and coordination costs are internal to firms, arbitrage implies that price p_h of the h good is simply $p_q - p_s$. Thus, we define $p_h \equiv p_q - p_s$ and the three prices are given by

$$p_q = \frac{2a + (m+n) + \Big(p_s\Big) \cdot \Big(\sum_h^m (1/\theta_h)\Big)}{\sum_i^n (1/\theta_i) + \sum_h^m (1/\theta_h) - 2b} \tag{6a}$$

$$p_s = \frac{\Big(p_q\Big) \cdot \Big(\sum_h^m (1/\theta_h)\Big) + (k - m)}{\sum_s^k (1/\theta_s) + \sum_h^m (1/\theta_h)} \tag{6b}$$

$$p_h \equiv p_q - p_s. \tag{6c}$$

2.2. **Long Run Cost Minimizing Industry Structure.** Throughout this paper, we use "long run" to mean the stationary state, by which we mean a state where all opportunities for profitable entry have been exhausted. Given our setup, the stationary state implies that all incumbents have the same minimum average costs, i.e., that all incumbents are maximally efficient. With exogenously specified transaction costs, if the diseconomies of scope within firms (γ) are lower than the cost of transacting over markets (2τ), only closed firms can survive so that the industry is completely dominated by closed firms, and the reverse if $\gamma - 2\tau > 0$.[3]

3. Simulating Industry Evolution

Though a long run equilibrium analysis is useful as a benchmark, one can ask whether and how rapidly it will be attained. Further, how do entry and exit affect convergence, and in particular, is the process of convergence symmetric between open and closed forms? Thus, to follow the evolution of the industry structure, we fixed different values of τ and γ across simulations such that $\gamma - 2\tau$ ranges from -2 to+2. For each value of $\gamma - 2\tau$, we ran 35 simulations. In addition, we also simulated over initial conditions, i.e., with equal numbers of H and S type firms but with different initial values of market share of closed firms (i) high ($MS_0 \simeq 0.9$), (ii) intermediate ($MS_0 \simeq 0.5$) and, (iii) low ($MS_0 \simeq 0.2$), where the market share of closed firms (MS), of the industry is defined as

$$MS \equiv \frac{\sum_i^n q_i}{\sum_i^n q_i + \sum_h^m q_h}. \tag{7}$$

The details of the design and algorithm and the parameter values used in the simulations are given in appendix 1. The parameter values used imply that fixed costs are about 33% of the total long run minimum average costs. The range of values for $\gamma - 2\tau$ over which the simulations are run are equivalent to about 40% of the total fixed costs.

3.1. **Entry, Exit and Iterations.** Following Jovanovic (1982), we assume "noisy" selection, where low cost firms survive and high cost firms exit.[4] Firms are assumed to be myopic. Potential entrants choose whether to enter as an integrated firm (I-type), a firm selling only component H (H-type), a firm selling only component S (S-type), or not enter at all. This decision is based only on the current market prices and their own efficiency parameters, θ_s and θ_h. Post entry, costs do not change (no learning), and if it becomes unprofitable to continue producing as a particular type over time, a firm exits rather than switch its organizational form. After an episode of entry, prices adjust. Incumbents who obtain negative profits exit, with the firm realizing the least profit exiting first. After each exit, the remaining firms evaluate their profits at the changed prices, as defined by equations [6] above, and if profits for some firms are still negative, the firm with the next lowest profit exits. This process is repeated until all remaining firms have non-negative profits. The last exit after each entry marks the end of a period (and one iteration in the simulation). Note that in our model, exit takes place sequentially, with prices recomputed after each exit. This process

[3]The reverse is true unless the industry starts out with only closed firms. In the latter case, the industry will be dominated by closed firms even if $\gamma - 2\tau > 0$, simply because we do not allow an S and H type firm to enter together.

[4]Following Jovanovic (1982) the model allows firms to differ in output due to differences in efficiency rather than in fixity of capital. However, we conjecture that our results are unchanged if firms differed in terms of fixed costs, instead of marginal costs. Following Porter (1980) & Klepper (1996), the efficiency parameter of firms is a random variable with a uniform and continuous distribution.

is repeated for 500 iterations and the entire process is called one simulation. Over 1000 such simulations were done for a range of parameter values and initial configuration of the industry.[5]

3.2. **Simulation Results.** In our simulations, the industry structure tends to be stable after 200 periods. Typically, at the end of 500 periods, the market price is 4-6% above its long equilibrium value, and the average total cost is about 1.5%-8.5% above the long run value and about 3% above the long run minimum cost when $\gamma - 2\tau = 0$. These simulations illustrate how the entry and exit processes can drive the industry structure away from its long run equilibrium. As we will see, the interim industry structure is very different from its long run state even with costs and prices close to their long term values.

Figure 1 plots the market share of I-type firms for the first 500 periods (iterations) from 5 "typical" simulations with different values of $\gamma - 2\tau$ and where the initial market share of closed firms is about half.[6] They are "typical" in the sense that for each of the exogenously set values of $\gamma - 2\tau$, 35 simulations were run and that a significant majority of each set of 35 resulted in a time path similar to the one shown in the figure.[7]

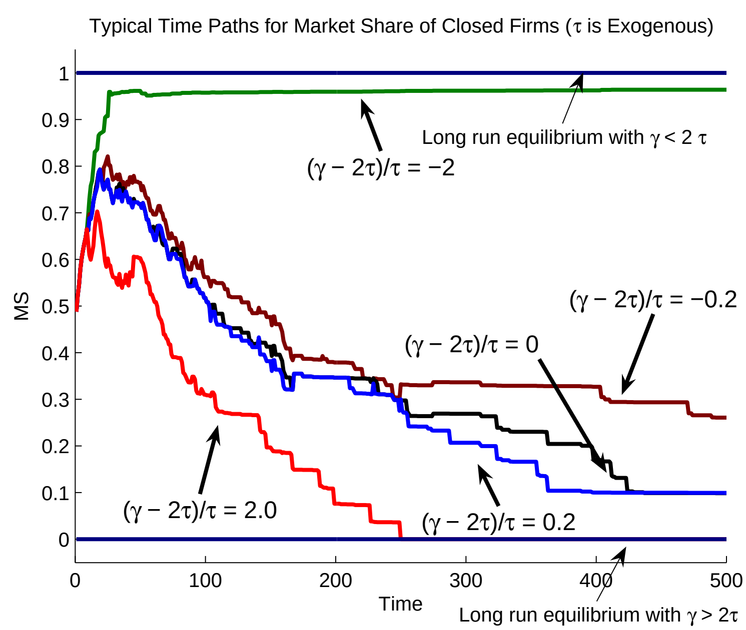

FIGURE 1. Typical time plots for market share of closed firms

[5]All in all, we ran over 2000 simulations including those with slightly different versions of the model, not reported in this paper, but with very similar results. For details of simulation design and algorithm see appendix 1.

[6]As mentioned earlier in the text, we also simulated over different initial values of market share. Results from these other initial conditions ($MS_0 \simeq 0.9$, $MS_0 \simeq 0.2$) were entirely consistent with those with initial market share being about 0.5 and hence in the interest of space we do not show or discuss those results in the paper.

[7]Thus, these are five actual outcomes and not average values of the outcomes from various simulations. The average values are shown and discussed later.

For all cases, τ was set equal to .25 (which is 25% of the fixed costs of an open firm). Thus $(\gamma - 2\tau/\tau) = -2$ corresponds to the case when γ is 0% of the fixed costs incurred by a closed firm and $(\gamma - 2\tau/\tau) = +2$ corresponds to the case when γ is 50% of the fixed costs of a closed firm. When the cost differences are large, it is not surprising that the industry evolves quickly towards the long run equilibrium, such that it is dominated by closed firms in the first case ($MS = 1$ by about 100th period) and by open firms in the second case ($MS = 0$ by about 250th period).

What come as a surprise are the other three cases when $\gamma \simeq 2\tau$. A number of things are worth noting here. First, when $\gamma = 2\tau$, there is no relative cost disadvantage to either type of firms. If the industry were to evolve monotonically towards a configuration which minimizes the long run average costs, then there is no reason to expect *a priori* that, when $\gamma = 2\tau$, *most* of the simulations would show the pattern in Figure 1, i.e., moving closer to $MS = 0$ (in fact, by the 500th period, the average value of market share of I-type firms was about 0.2).

Second, when γ is slightly less than 2τ, i.e., the case when $(\gamma - 2\tau/\tau) = -0.2$, closed firms still have a cost advantage (γ is 22.5% of the fixed costs and τ is 25% of the fixed costs), and so in the long run, the industry should be completely dominated by closed firms with $MS = 1$. Yet, the simulations show that except for the initial periods, the industry still evolves away from the value of $MS = 1$. In fact, up until the 500th period, the market share of closed firms is still falling, albeit very slowly beyond the 250th period.

Third, in almost all simulations, the market share of I-type firms initially increases, showing that a closed configuration was more likely very early in the history of the industry. Even in the cases when the final value of MS must equal zero (e.g., $(\gamma - 2\tau/\tau) = +2$), the industry does not monotonically evolve towards the long run cost minimizing structure.

In summary then, the figure shows that when $\gamma - 2\tau$ is negative but small, MS moves away from its steady state value of 1, at least for the duration of the simulation. However, when $\gamma - 2\tau \ll 0$, MS evolves towards its steady state value of 1. By contrast, for $\gamma - 2\tau > 0$, MS tends towards zero. Our simulations also revealed that in virtually every case, closed entry was more likely very early in the history of the industry when prices are high.

To get a better sense of how "typical" these simulations are (as well as how frequent are the cases when the industry evolves in non-typical ways), Figure 2 provides the average value of MS from the many simulations for each value of $\gamma - 2\tau$. The error bars are the standard deviation of the mean. The average values are reported from select periods and moving from the flat line (0th period) through the steepest line (500th period) provides the evolution of the averages.[8] When

[8]Our simulations showed that 35 runs per value of $\gamma - 2\tau$ were enough to give us the asymptotic distributions. As a check, we ran 35 additional simulations for selected values of $\gamma - 2\tau$. Not only did the mean and the standard deviation remain substantially unchanged (differences were of the order of 1-2%), the entire distribution did not change by much either.

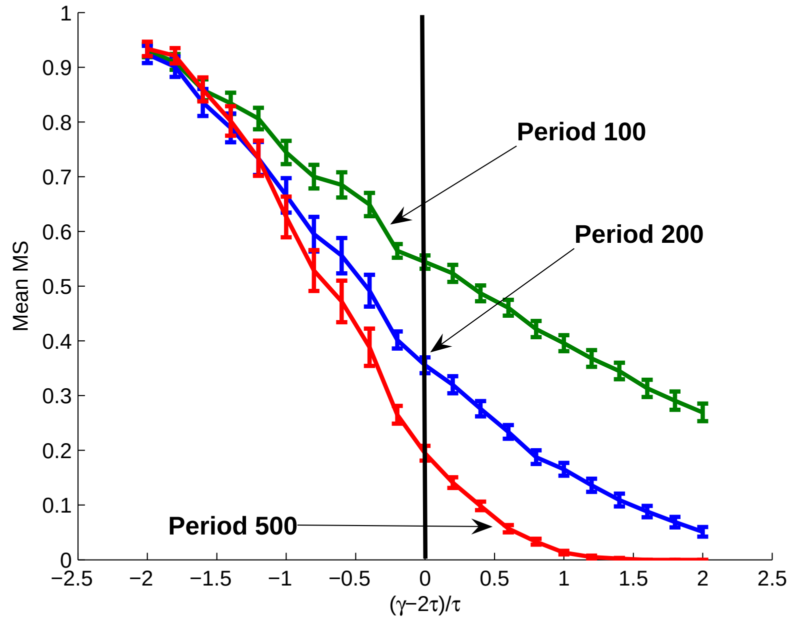

FIGURE 2. Snapshots of average MS, for exogenous τ and γ

open firms have a cost advantage ($\gamma - 2\tau > 0$), the industry becomes dominated by open firms early (observe for instance the snapshot from the 200th period) and any increases in the extent of the cost difference, $\gamma - 2\tau$, do not have an appreciable effect on MS outcomes by the later periods. By contrast, when closed firms have a cost advantage ($\gamma - 2\tau < 0$), as long as the cost advantage is small ($|\gamma - 2\tau/\tau| < .5$), the industry configuration continues to be mixed: Open firms are likely to have a substantial market share even as late as the 500th period. In particular, when $\gamma = 2\tau$, the average market share of closed firms in the industry is only about 20%, well below the 50% that one might expect. Finally, there is more variation in the evolution path of the industry (and hence more deviations from the "typical" paths reported in Figure 2) when there is a *small* cost advantage in favor of the closed firms (e.g. $0 > \frac{\gamma-2\tau}{\tau} > -.5$) compared to the case when there is a *small* cost advantage in favor of open firms (e.g. $.5 > \frac{\gamma-2\tau}{\tau} > 0$), i.e., error bars slightly to the left of the zero line are much larger than the error bars slightly to the right.

To get additional insight as to how the industry evolves, we recorded and analyzed other statistics as well. Among the more important ones are the price and efficiency parameters. The top two panels of Figure 3 show the average values of $p_q/2$ and p_s at selected time periods (300, 400 and 500) while the lower two panels show the average efficiencies for the closed firms (divided by 2) and the S-type open firms (the results for the efficiency parameter of the H-type firms are almost identical to those for the S-type and hence are not shown). Again, the values shown are the average over the 35 simulations for the given value of $\gamma - 2\tau$, with the bars indicating the standard deviation of the

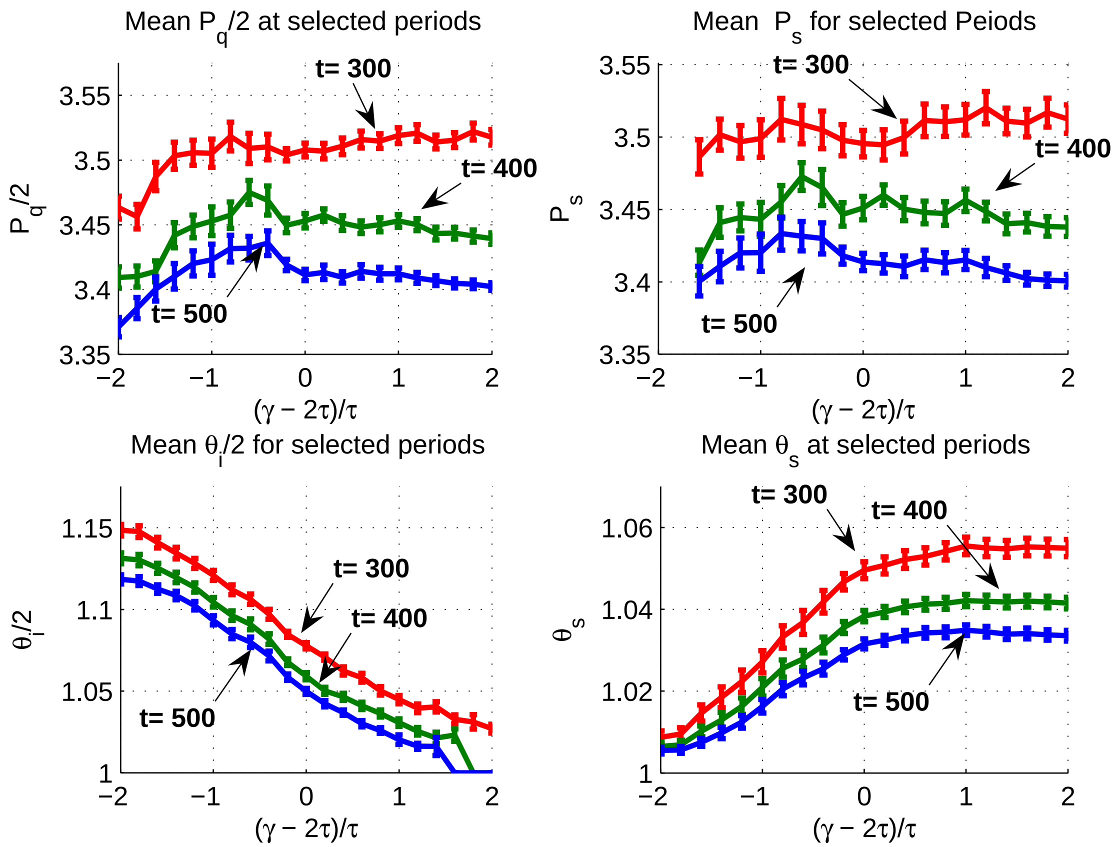

FIGURE 3. Snapshots of mean prices p_q, p_s & efficiency parameters θ_i and θ_s

mean.[9] Note that there is an asymmetry in lower two panels of Figure 3, i.e., the average value of θ_s is lower, the lower is $\gamma - 2\tau$ when closed firm is more efficient but remains largely constant for $\gamma - 2\tau$ positive. By contrast, the average θ_i for the I-type firms is higher, the lower is $\gamma - 2\tau$.

4. EXPLAINING THE DYNAMICS

Setting aside the non-interesting case when there is a large cost advantage to either open or closed firms (extreme left or extreme right positions on the previous graphs), the simulation results have two main features: (1) The dynamic processes are asymmetric. When there is a small cost advantage to closed firms, convergence towards the long run cost minimizing configuration is slower and more uneven compared to when there is either a small cost advantage or no advantage to open firms. Also, the prices are higher in the former case. (2) Closed entry is more likely than open entry early

[9] The prices at extreme left are lower than the prices at extreme right because of the way the values of $\gamma - 2\tau$ were varied over the simulations and reflect the differences in fixed costs. Specifically, in all simulations τ was fixed at 0.25 and γ varied from 0 to 1 in increments of 0.05 thus making the difference $(\gamma - 2\tau)/\tau$ vary from -2 to + 2. Thus at extreme left $((\gamma - 2\tau/)\tau = -2)$, the total non-variable cost to a closed firm firm is $\alpha + \beta + 0$ and the total non-variable cost incurred by two complementary open firms (an H-type and an S-type) is $\alpha + \beta + 2 * .25$. At the center, $((\gamma - 2\tau/)\tau = 0)$, the non-variable costs to closed and complementary open pair are $\alpha + \beta + 2 * .25$ and $\alpha + \beta + 2 * .25$ while at the extreme right $((\gamma - 2\tau/)\tau = +2)$ these costs are $\alpha + \beta + 1$ and $\alpha + \beta + 2 * .25$ respectively. For more details, see the appendix with details on simulation design.

in the industry life cycle but the odds of closed entry fall over time. Our explanation of the observed dynamic patterns has three parts.

First, we explore the entry conditions. Here we show that closed firm entry takes place because of the opportunity to capture multiple profits but that the probability of capturing multiple profits is lower than the probability of positive profits in one activity (we call this the "Babbage effect). Further, that while the odds of closed firm entry (relative to open firm entry) are initially greater than one, they monotonically decrease in prices. As prices fall below a threshold value, the relative odds fall below one and keep decreasing with a decrease in prices. Hence, the odds of closed form entry become smaller as the industry evolves.

Second, we explore the exit conditions. We show that the exit process for closed firms is different from the entry process. Specifically, because a closed firm only enters if both components are profitable, it enters if the *product* of two random draws is below a threshold value that depends on the prevailing price. On the other hand, a closed firm stays in the industry as long as the *average* of two random draws is lower than a price-dependent threshold value. This contrasts with the situation of open firms which exit as soon as their single random draw becomes too low. This is because the CDF of the average of two iid random variables has thinner tails than the original CDF, and thus cuts the original CDF from below. To see this in the context of the distributions used in the simulation, note that the CDF of the average of two uniform draws (which is an S-shaped CDF of a triangular PDF) cuts the CDF of a single uniform draw from below (the CDF of a uniform distribution is a 45^o straight line between 0 and 1). This implies that the probability of exit of a closed firm is greater than the probability of exit of an open firm when the price-dependent threshold is to the left of the intersection point of the two CDFs and is less when the price-dependent threshold is to the right of the intersection. Thus, when prices are high, since the threshold is to the right of the intersection of the CDFs, a closed firm has a lower probability of exit than an open firm that entered at the same time. As prices fall, however, the situation is reversed (the threshold moves to the left of the intersection) and the closed firm has a higher probability of exit.

Finally, we also show that there is yet another process that favors open firms. We call this the complementarity effect and show that if either the size or efficiency of component sectors are not equal, then the probability of entry by a closed firm is lower than if the size and efficiency of the two complementary open firm sectors are equal.

4.1. **Entry Conditions.** The entry conditions for the potential entrant (and the exit condition for incumbents) can be derived from non-negative profit requirement. Thus, a necessary condition for entry is that a potential entrant draw an efficiency parameter such that with the given prices, p_q and p_s, it should earn non-negative profit. Using $\alpha = \beta = 1$, the threshold value for an H-type or

S-type firm to make zero profit is

$$\theta_h^c = (p_q - p_s) + 2(1+\tau) - 2(1+\tau)^{1/2}(p_q - p_s + 1 + \tau)^{1/2} \tag{8a}$$

$$\theta_s^c = p_s + 2(1+\tau) - 2(1+\tau)^{1/2}(p_s + 1 + \tau)^{1/2} \tag{8b}$$

and for an I-type firm it is

$$\theta_i^c = p_q + 2(2+\gamma) - 2(2+\gamma)^{1/2}(p_q + 2 + \gamma)^{1/2}. \tag{8c}$$

Entry for a k type firm requires that the potential profit be non-negative ($\theta_k \leq \theta_k^c$) and that it be greater than the potential profit as any other type of entry.

Condition 4.1 (Sufficient Entry Condition). For a potential entrant to enter as type k, where $k = i, h, s$, it must be true that

$$\Pi_k^*(\theta_k) = Max\{\Pi_s^*(\theta_s), \Pi_h^*(\theta_h), \Pi_i^*(\theta_i), 0\}. \tag{9}$$

Given the functional forms of our cost functions (equations [2,3]), then with $\gamma = 2\tau$ it is always true that

$$\Pi_i^*(\theta_i) \leq \Pi_s^*(\theta_s) + \Pi_h^*(\theta_h). \tag{10}$$

This inequality arises because the efficiency parameters enter the cost functions multiplicatively with quantity. As a result, the efficiency parameters also enter the marginal costs (i.e., $C_s'(q_s, \theta_s) = (2q_s+1)\theta_s$, $C_h'(q_h, \theta_h) = (2q_h+1)\theta_h + p_s$ and $C_i'(q_i, \theta_i) = (2q_i+1)\theta_i$). This implies that a closed firm, which must produce the same level of both components, will not produce at the efficient level of either h or of s (the levels it would produce if it produced to an open standard). As an illustration, let $\theta_s = 1$ and $\theta_h = 2$, and $p_q = 12, p_s = 6$, so that $p_h = 6$ as well. Then the profit maximizing quantities for the S and H firms are 2.5 and 1 respectively, and their marginal costs are 6 and 6. A closed firm has to produce equal amounts of the two components. Thus, it will produce 1.5 units, with a marginal cost of 4 in the s activity and a marginal cost of 8 in the h activity. The closed firm under produces s and overproduces h, and therefore the profits are less than the sum of the profits if it were to split into two independent firms. Formally, we can state the following proposition.

Proposition 4.1 (Division of Labor Effect (DoL)). Let $\Pi_j^*(\theta_j)$ be the maximized profits of a j type firm where $j = i, s, h$. Then $\gamma - 2\tau = 0$ implies that

$$\Pi_i^*(\theta_h + \theta_s) \begin{cases} < \Pi_s^*(\theta_s) + \Pi_h^*(\theta_h) \text{ if } \frac{\theta_h}{\theta_s} \neq \frac{p_q - p_s}{p_s} \\ = \Pi_s^*(\theta_s) + \Pi_h^*(\theta_h) \text{ otherwise.} \end{cases}$$

Proof. See appendix 1. □

Stigler (1951) highlights this effect in his analysis of division of labor among firms. In our model this division of labor effect arises because of heterogeneity in the efficiency parameters, and because the efficiency parameters enter the cost function multiplicatlvely. However, in our simulations this effect was small, i.e., the observed potential profit for a closed entrant was usually almost equal to the sum of profits of two complementary open entrants.[10] Since

$$\Pi_i^*(\theta_i) \approx \Pi_s^*(\theta_s) + \Pi_h^*(\theta_h),$$

then in order to isolate other effects analytically, we will just neutralize this small effect by assumption. Specifically, henceforth we will assume that the above relation is a strict equality, i.e., the "division of labor" effect is not present. Given this assumption, we can now state the (modified) sufficient entry conditions.

Proposition 4.2 (**Modified Entry Conditions**). Let $F_h(\theta_h)$ and $F_s(\theta_s)$ be the distributions of θ_h and θ_s, then ignoring the division of labor effect (i.e., let $\Pi_i^*(\theta_i \equiv \theta_h + \theta_s) = \Pi_s^*(\theta_s) + \Pi_h^*(\theta_h)$),

(1) the probability of closed firm entry is $F_h(\theta_h^c).F_s(\theta_s^c)$ and,
(2) the probability of H-type entry is $F_h(\theta_h^c).\{1 - F_s(\theta_s^c)\}$ and similarly the entry of S-type entry is $F_s(\theta_s^c).\{1 - F_h(\theta_h^c)\}$, where

θ_h^c, θ_s^c are as given in Equations [8].

Proof. See appendix 1. □

For the uniform case and under the modified entry conditions (proposition 4.2) the probabilities of entry are $Pr(I\text{−type enters}) = \theta_h^c\theta_s^c - \theta_h^c - \theta_s^c + 1$ and similarly $Pr(H\text{−type enters}) = 2\theta_h^c + \theta_s^c - 2 - \theta_h^c\theta_s^c$ and $Pr(S - \text{type enters}) = 2\theta_s^c + \theta_h^c - 2 - \theta_h^c\theta_s^c$.

Proposition 4.3 (**Corollary to Proposition 4.2**). $\Pi_i^*(\theta_i \equiv \theta_h + \theta_s) = \Pi_s^*(\theta_s) + \Pi_h^*(\theta_h)$ together with the sufficient entry conditions (equation 9) imply that

(1) a potential entrant enters as an I-type firm if and only if $\theta_h < \theta_h^c$ and $\theta_s < \theta_s^c$ and,
(2) a potential entrant enters as a specialized H-type firm if and only if $\theta_h < \theta_h^c$ and $\theta_s \geq \theta_s^c$ and as an S-type firm if and only if $\theta_h \geq \theta_h^c$ and $\theta_s < \theta_s^c$.

Proof. See appendix 1. □

Observe that if a potential entrant draws values of θ_h and θ_s such that $\theta_h \leq \theta_h^c$ and $\theta_s \leq \theta_s^c$, then there are positive profits to be made in each activity. Since $\Pi_s^*(\theta_s)$ and $\Pi_h^*(\theta_h)$ are each positive, $\Pi_i^*(\theta_i) > \Pi_s^*(\theta_s)$ and $\Pi_i^*(\theta_i) > \Pi_h^*(\theta_h)$. Simply put, in our model closed firm entry takes place because of the opportunity to capture two profits. As we show below, the probability that the firm will be good enough in both relative to being good enough in any one component falls as prices fall. Thus, while the closed firm entry takes place because of the opportunity to capture multiple profits, there exists a range of threshold values over which the probability of drawing two efficiency parameters such that positive profits can be realized in each activity is lower than the probability of realizing positive profits in one activity. Hence the following proposition.

[10]Moreover, this effect would disappear altogether with alternative specifications. For instance, if we had specified cost functions where the efficiency parameters entered the cost additively (e.g., to the fixed cost), and marginal cost was constant, then the profit of a closed firm would always be equal to the sum of the profits of two complementary open firms.

Proposition 4.4 (**Babbage Effect**)**.** For $\gamma = 2\tau$, there exists a non-empty subset $\Theta \subset \theta_s \times \theta_h$ such that for all $(\theta_s, \theta_h) \in \Theta$, the relative odds of closed entry (relative to open)

$$\eta = \frac{F_s(\theta_s^c)F_h(\theta_h^c)}{F_h(\theta_h^c)\{1 - F_s(\theta_s^c)\} + F_s(\theta_s^c)\{1 - F_h(\theta_h^c)\}}$$

are greater than one.

Proof. See appendix 1. □

Proposition (4.4) shows that for any arbitrary distribution of θ_h and θ_s, there is a threshold level of efficiency, such that the probability that a potential entrant is efficient (draws a value below the threshold) at either s or h, is greater than the probability that he is efficient at both. When prices drop, the maximum value of θ_h and θ_s falls, reducing the likelihood that an entrant can enter as an s or h type firm. The probability that an entrant can enter as a closed firm, i.e., that θ_h and θ_s are both smaller than the corresponding threshold values, falls even faster. More formally, we show below that if the prices are still high enough to allow any type of entry, then the odds of closed entry (relative to specialized entry) fall with prices.

Proposition 4.5 (**Evolution of the Babbage Effect**)**.** For $\gamma = 2\tau$, the odds of closed entry (relative to open entry) fall with prices p_q and p_s (and where, recall that $p_h \equiv p_q - p_s$).

Proof. See appendix 1. □

Propositions (4.4) and (4.5) help explain the two most important aspects of our simulations: (1) initially the market share of closed firms increases because prices are high enough that the relative odds of closed firm entry are greater than one and (2), as the system evolves and the prices fall, the relative odds of closed firm fall below one and go on decreasing so that the market share of closed firms keeps falling.

We confirm the results of the proposition above numerically as well by showing that the relative odds of closed firm entry fall with prices. Figure 4, which is drawn for a symmetric path with $p_q = 2p_s$, shows that for high prices, the conditional probability of closed entry (conditional on some entry) is high and drops as prices drop. The larger the value of $\gamma - 2\tau$, the greater the conditional probability of closed entry for any given price. When the advantage to closed firms is only modest, the conditional probability can drop below 0.5 implying that "balanced" open firm entry (entry by an open firm followed by a complementary open firm entry in the next period) is more likely than entry by a closed firm. However, when closed firm entry is the efficient form in the long run, eventually prices fall enough to choke off open firm entry while still leaving room for closed firm entry.

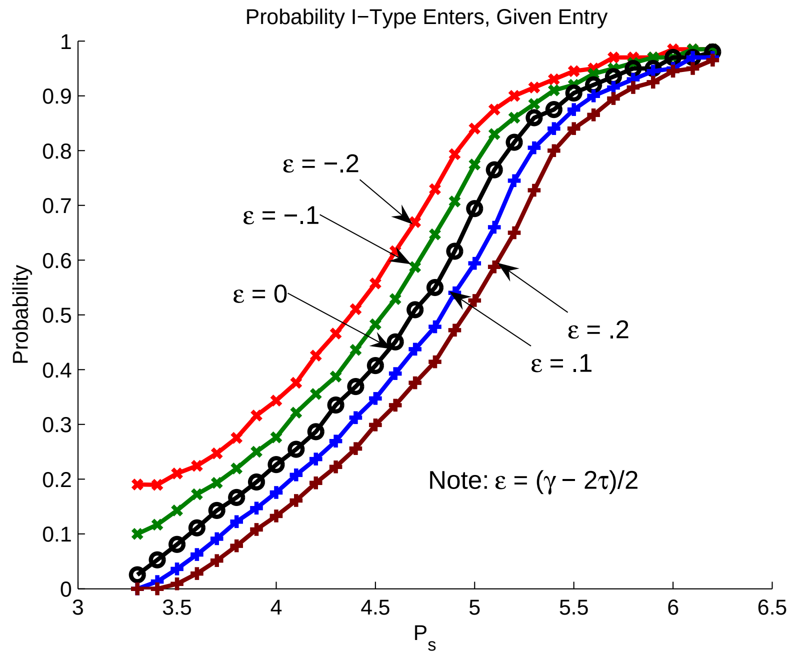

FIGURE 4. Probability (I-Type Enters|Given Entry)

4.2. **Exit Conditions.** Exit for open firms is similar to entry in that an open firm exits when its efficiency falls below a threshold i.e., when $\theta_l, l = i, h, s,$ is larger than the threshold parameter. This is analogous to the entry process. Exit for a closed firm, however, is different. It exits if its average efficiency in the two activates combined is below the average threshold. An immediate implication is that a closed firm may survive even if its efficiency in one activity is below the open firm's threshold provided it is sufficiently more efficient in the other activity. This implies that initially, a closed firm may be better able to survive relative to an open firm. However, as prices fall, this advantage dissipates. Intuitively, initially a closed firm can offset losses in one activity with profits in another. This implies that initially, it is less likely to exit than an open firm that entered under similar conditions. Thus, as prices fall, the losses in the inefficient activity will increase even as profits in the efficient activity fall. Although profits for open firms will also fall, open firms do not have to subsidize loss making activities. Thus open firms, specialized in one activity only, are better able to cope with lower prices. As we discuss below, this reflects the differences between the distribution of the average of independent random variables. Compared to the original distribution, the distribution of the average has "thinner" tails.

Restricting ourselves to the symmetric case (where $p_s = p_h$, and where $\gamma = 2\tau$, so that the entry thresholds are the same), consider the thought experiment where we follow a newly entering closed firm and a newly entering open firm.[11] Since the thresholds are the same (i.e., $\theta_s^c = \theta_h^c = \theta_i^c/2 = \theta^c$),

[11]In our simulations we allow at most one entry per period so this thought experiment is best thought of as comparing across two simulations that are identical up to some period $t-1$. Then in period t, in one case, a closed firm enters and in another, a open firm enters.

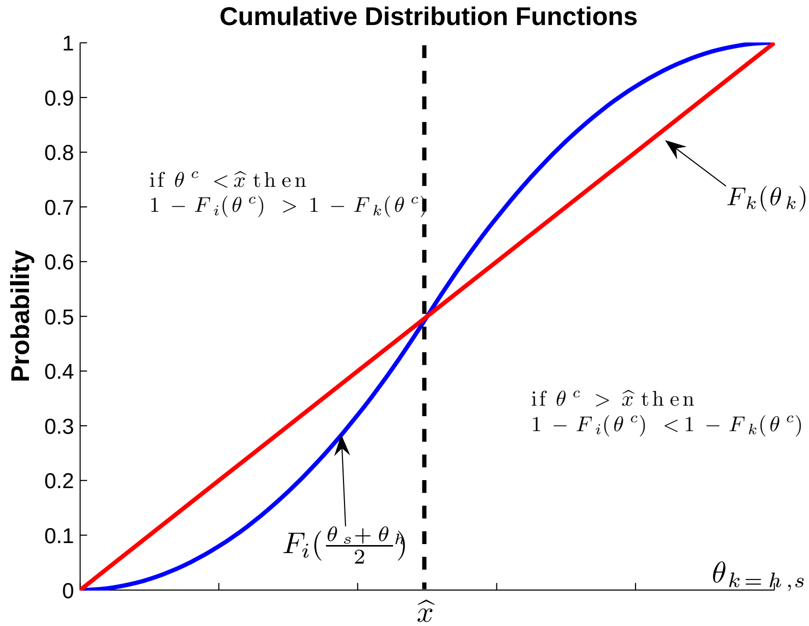

FIGURE 5. Exit Probabilities

the modified entry conditions imply that $Pr(\theta_l < \theta_l^c)$ where $l = s, h, i$ is the same for all types of firms.

Let the distribution of θ for the open firms be $F_k(.)$ where $k = s, h$. Then the probability distribution function for the average efficiency of an entering closed firm is $Pr(\theta_s + \theta_h < 2x) = Pr((\theta_s + \theta_h)/2 < x) = F_i(x)$. The probability that the open firm will exit if the maximum permissable value of θ is θ^c is equal to $1 - F_k(\theta^c)$. For the closed firm, it is equal to $1 - F_i(\theta^c)$. Note that $(\theta_h + \theta_s)/2$ is the average efficiency of the closed firm. Note further that $F_i(.)$ second order stochastically dominates $F_k(.)$. Intuitively, as an average, $(\theta_s + \theta_h)/2$ has the same mean as θ_s and θ_h, but has "thinner" tails. This implies that $F_i(.)$ cuts $F_k(.)$ from below, implying that there is some $\widehat{x}$, such that $x < \widehat{x}$ implies $F_k(x) > F_i(x)$ and $x > \widehat{x}$ implies $F_i(x) > F_k(x)$ (see Figure 5). It follows that, after entry, there is some period where the probability of exit for open firms is $1 - F_k(\theta^c)$ which is greater than the probability of exit for closed firms, $1 - F_i(\theta^c)$, which is true as long as $F_k(\theta^c) < F_i(\theta^c)$, which is true as long as $\theta^c > \widehat{x}$. However, once prices fall sufficiently such that $\theta^c < \widehat{x}$, then the probability of exit for a closed firm is higher than the probability of exit for the open firm. In other words, not only are closed firms more likely to enter in the early stages of the industry, they are also less likely to exit as compared to open firms that managed to enter early. However, as the industry evolves and prices fall, not only does entry become more difficult, exit becomes more likely as compared to open firms.

This comparison provides some additional intuition for our results. However, since the firms in the market at any given time consists of a mixture of firms that entered at different times and survived, and since closed and open firms have different relative probabilities of entry and exit over time, it is not easy to analytically characterize what happens to the exit probabilities of surviving firms. The difficulty is even higher if we consider cases where γ is different from 2τ or where p_s is not equal to p_h.

4.3. **Complementarity effect.** When an S or H type firm enters, it always improves the relative odds of entry by a complementary open firm. This is because if an S type firm enters, p_s falls making it harder in the next period for another S type to enter, but since p_s is an input price for H type firms, it increases the probability of an H type firm. Hence an imbalance between the number of S and H types in the market makes open entry into the smaller sector more likely and open entry into the larger sector less likely. Moreover (and more importantly) if the distribution function of $\theta_k, (k = s, h)$ is concave, an imbalance between the two open sectors increases the probability of open entry relative to closed entry. If the relative size and (average) efficiency of the two complementary sectors is almost equal, then this effect tends to be short lived. However, the effect is important when the size or efficiency of the two complementary sectors are unequal. If this difference in sectors is large, the complementary effect can persist. We state this more formally in the following proposition.

Proposition 4.6 (**Complementarity Effect**)**.** If either the size or efficiency of the complementary open sectors are not equal (i.e., $n_s \neq n_h$ or $\sum(1/\theta_s) \neq \sum(1/\theta_h)$) then it implies that $\theta_s^c \neq \theta_h^c$. Further, if F'/F is monotone decreasing (where $F(.)$ is the CDF for θ_h and θ_s), then

$$Pr\big(\text{I-type enters}|\ \theta_s^c = \theta_h^c, \theta_s^c + \theta_h^c = \rho\big) > Pr\big(\text{I-type enters}|\ \theta_s^c \neq \theta_h^c, \theta_s^c + \theta_h^c = \rho\big)$$

Proof. See appendix 1. □

Put differently, if the two open complementary sectors are of unequal size or efficiency, then the probability of closed entry is lower than if the complementary open sectors were of equal size and efficiency. This is so because when the open complementary sectors are not of equal size, then the critical entry thresholds θ_s^c and θ_h^c are not equal. Since the probability of closed entry is given by $F(\theta_s^c)F(\theta_h^c)$, then when the thresholds are equal, this is just the square of $F(\theta_k^c)$. For convex functions, it is possible that the square is smaller than the product of two probabilities. For example, let θ_k^c be the average of θ_h^c and θ_s^c. Then for some very convex distribution function, it is possible that $F(\theta_k^c) = .2, F(\theta_s^c) = .1$ and $F(\theta_h^c) = .9$ giving the condition that the square is less than the product, i.e., $F(\theta_k^c)F(\theta_k^c) < F(\theta_s^c)F(\theta_h^c)$. However, for concave distribution functions (and more generally, for distribution functions with F'/F monotonically decreasing), it is guaranteed that the square of $F(\theta_k^c)$ is greater than the product of $F(\theta_s^c)F(\theta_h^c)$.

Note that the condition that the distribution function be concave is stronger than needed. In fact all that is needed is that the distribution function be such that F'/F is monotonically decreasing (see the proof) which is equivalent to requiring that $F()$ be log concave. Thus, necessary and sufficient for our result is that $F()$ be log concave, and is satisfied for a number of distributions including uniform, normal and exponential distributions.[12] A more geometric interpretation is that the cumulative distribution be either concave (because then the condition $F.F'' < F'^2$ is automatically satisfied since for concave functions $F'' \leq 0$) or that if it is convex (in the region around $\rho/2$) then the curvature be not too large.[13] The precise condition, derivable from the second order condition $F.F'' < F'^2$, is that the radius of the osculating circle (i.e., radius of the curvature) be greater than $\sqrt{1+F'^2}(\frac{1+FF''}{F''})$.

5. Robustness and Extensions

In this section we explore how our results would be affected if we were to relax some of the assumptions used in the analysis and discuss possible extensions of the analysis.

5.1. **Myopic decision making.** Assuming myopic decision making greatly simplifies our analysis. Given the uncertainty in the environment and the possibility of multiple equilibrium paths, making fully forward looking decisions is costly and difficult. Moreover, myopic decision making is almost rational, due to assumptions already made in the model: firms are price takers, there is no 'learning', and sunk costs are absent. Introducing forward looking behavior will not affect the output decision since there is no learning and no strategic behavior. There is possible option value to entering the market (or staying in), however this value is small since, but for jumps caused by the lumpiness of entry and exit (the number of firms is an integer), prices would never rise over time.[14] Thus, if current profits are negative, then future profits would also be negative, implying an option value of zero associated with entry or 'staying in'.

Forward looking behavior could conceivably affect the decision on the form of entry. Indeed, allowing for more sophisticated forward looking behavior could further reinforce the bias in favor of open configuration. In our model, if the industry starts out heavily dominated with closed firms, it tends to remain as such: An open firm typically faces a very inefficient complementary sector and therefore cannot enter unless its own efficiency is very high. In the extreme case, a potential open entrant may be unable to enter if there is no complementary supplier. However, a forward looking entrant would rationally forecast the entry of a complementary firm in the future, and therefore,

[12] Log concavity of distribution functions is a widely used assumption in economics. For an application in the theory of contracts, see Lafont and Tirole (1988) or for its application to the theory of auctions see Myerson and Satterthwaite (1983)

[13] The *curvature* for a function $y = F(x)$ at a point x is given by $\kappa = d^2y/dx^2/\{1 + (dy/dx)^2\}^{3/2}$, and the *radius of the curvature*, is defined as $R \equiv 1/\kappa$. This radius is in fact equal to the radius of the osculating circle at the point x. For relatively flat curves, the curvature is small and the radius R is large.

[14] Prices may rise briefly because of the interaction effects. For instance, the entry of an H-type will raise p_s. Similarly, exit by an S-type may trigger exit by an H-type, which may trigger further exit by an S-type. In principle, this feedback effect could cause large scale exit and large jumps in price as well. However, we did not observe such outcomes in the three thousand odd simulations that we ran.

would enter if its own efficiency were high enough. In other words, we conjecture that allowing for forward looking firms might further accentuate the dynamics observed.

5.2. **Closed firms produces equal quantities of both quantities.** This is a natural assumption, if, as assumed here, closed firms produce to a proprietary standard that is incompatible with the open standard. However, even if one were to allow closed firms to sell surplus quantities of one component to others, thereby allowing closed firms to produce each component at the efficient level, it would not materially affect our results. As already noted, this "division of labor" effect is small in our simulations, and our formal propositions do not rely upon it.

5.3. **Open firms do not produce both components.** We assume that an open firm specializes in one of the two components. Though unrealistic, this is a modeling device to allow closed firms to capture two profit margins but restrict open firms to only one. As noted earlier, we need this because there is no other source of advantage to being closed. Since our results indicate that the industry evolution favors open configurations, allowing open firms to produce both components would only strengthen this tendency. Indeed, for γ less than or equal to 2τ, no closed firms would ever emerge. An alternative would be to assume that closed firms enjoy a cost advantage. Our existing results provide insight into the implications of providing such a cost advantage and allowing an open firm to produce both components. In our model, that would amount to focusing on the parameter space where $\gamma < 2\tau$. In particular, when γ is below 2τ but the difference between them is not large, there is a long term advantage to the closed configuration. Allowing open firms to produce both components would mean first that the initial dominance of closed firms would be much less pronounced and open firms may dominate in the early history of the industry as well. With entry, prices fall and the "two profit margins" effect diminishes. Thus, we conjecture that the industry configuration would closely resemble the pattern reported here, albeit with a higher market share for the open configuration early in the history of the industry and perhaps a slightly higher market share for the open configuration later as well.

5.4. **Learning by doing and cost reduction over time.** Many models of industry evolution allow firms to reduce costs, either as a function of cumulative output or through systematic investments (e.g., Klepper (1996)). In these models, early entrants have an advantage: They have more time to learn and, with convex investments costs, can spread the investment cost over time. This intuition suggests that allowing firms to reduce costs in our model may imply that closed industry structures may persist since initially entry and exit conditions are favorable for closed firms. Another way to model such persistence is to allow transaction costs themselves to depend upon the volume of transactions. With endogenous transaction costs, an open industry configuration is always socially more efficient in our model. However, simulations (not reported here) strongly suggest that closed industry structure can be the long run equilibrium, particularly if the industry starts with a high degree of market share of closed firms. It is likely, as in Farrell, Monroe, and Saloner (1998), that a closed industry structure may be even more likely if incumbent closed firms can take actions to lower the share of open firms and raise the level of transaction costs.

5.5. **Stable demand.** To ensure that the long run equilibria are reached quickly, we deliberately model demand as fixed. Growth in demand would moderate the fall in prices over time and therefore prolong the initial phase wherein closed firms dominates. However, as long as demand grows slowly enough, we conjecture that our basic findings would remain unchanged.[15]

6. Summary and Conclusions

In recent years, often inspired by events in the information technology sector, there has been much discussion about whether particular markets will be dominated by open or closed systems. Sometimes this distinction is phrased in terms of the merits of "best of breed" combinations of components contrasted with the advantages of integrated product suites. In other cases, this issue is cast in terms of compatibility of components, or of open versus closed standards. In this paper, we assume that there is one open standard, and multiple closed standards, each specific to the firm producing a closed product.

The choice between open and closed standards depends on several considerations. The traditional view has emphasized how closed systems can yield lower costs by economizing on coordination and transactions across firm boundaries. In some cases, closed systems may also provide the seller with better pricing power. In the traditional view, closed systems would dominate if these advantages stemming from transaction cost economies are significant. A more recent literature has examined the role of heterogeneity in preferences of consumers, and in that context, of the "toughness of competition". Open systems typically allow for greater variety by allowing users to "mix and match", but may also result in tougher price competition. However, in focusing on equilibrium outcomes with a given number of firms, the literature has not analyzed the role of entry and exit, which is the focus of our paper.

We assume that closed firms, which produce to a proprietary standard, must produce all the required components, whereas firms producing to an open standard specialize. Our point of departure is Charles Babbage's observation that specialization implies that one does not have to acquire competencies in all activities, or equivalently, that acquiring a broad array of competencies is more

[15]Allowing for demand shocks would open the door to the situation where prices may rise for some period, and implies a positive option value for entering (or staying in) the market. This makes the myopic decision making assumption less tenable and the industry structure may take longer to approach its long run cost minimizing level. However, this should not bias our findings.

difficult than acquiring only a few competencies, and hence less likely to happen. Furthermore, once in the market, an open firm is likely to survive lower prices better than a closed firm. This difference in the likelihood of being able to acquire multiple competencies manifests itself over time, as the industry moves towards its long run equilibrium, but not at the long run equilibrium itself. To highlight the role of differences in capabilities, we develop a simple model with price taking firms, where entry and exit take place over time, and focus on how an industry evolves over time.

Our results point to the limitations of the transaction cost perspective on industry configuration. Though transaction costs do determine the long run equilibrium configuration, the industry does not evolve monotonically towards it. In particular, when closed systems are only slightly more efficient in the long run than open systems, the short term dynamics in favor of open configurations can cause the industry to evolve away from its long run equilibrium. This divergence persists even as prices come close to their long run equilibrium values. This divergence is therefore interesting because should further entry into an industry be stopped for any reason, the industry configuration would differ from its long run state.

Finally, our findings argue for a more cautious application of long run cost minimization to infer the industry configuration. Open configurations involve coordination of decisions. When these decisions are made by firms that enter and exit over time, the dynamic evolution of the system may be conditioned by its current state, and not simply by its long run equilibrium.

Appendix 1

Proof of Proposition 4.1. One can write $\Pi^i(\theta_i) = \Pi^s(\theta_s, q(\theta_i)) + \Pi^h(\theta_h, q(\theta_i)) + (\gamma - 2\tau)$, where $\Pi^s(\theta_s, q(\theta_i))$ are the profits of the s type when it produces quantity $q(\theta_i)$. By definition, $\Pi^s(\theta_s, q(\theta_i)) \leq \Pi^s(\theta_s)$. Further, the inequality is strict whenever $\frac{\theta_h}{\theta_s} \neq \frac{p_q - p_s}{p_s}$. By a similar argument, $\Pi^h(\theta_h, q(\theta_i)) < \Pi^h(\theta_h)$. The result follows directly.[16] □

Proof of Proposition 4.2. Since $\Pi_i^*(\theta_i \equiv \theta_h + \theta_s) = \Pi_s^*(\theta_s) + \Pi_h^*(\theta_h)$, closed firm entry implies that $\Pi_s^*(\theta_s) > 0$ and $\Pi_h^*(\theta_h) > 0$. Hence the probability of closed firm entry is given by $Pr(\theta_s < \theta_s^c \text{ and } \theta_h < \theta_h^c)$. Since θ_h and θ_s are independent, hence $Pr(\theta_s < \theta_s^c \text{ and } \theta_h < \theta_h^c) = Pr(\theta_s < \theta_s^c) \times Pr(\theta_h < \theta_h^c) = F_h(\theta_h^c).F_s(\theta_s^c)$. The proof for open S or H entry is similar. □

Proof of Proposition 4.3. For statement (1): Let $\theta_h < \theta_h^c$ and $\theta_s < \theta_s^c$. Then $\Pi_s^*(\theta_s) > 0$ and $\Pi_h^*(\theta_h) > 0$. Since both profits are greater than zero and $\Pi_i^*(\theta_i \equiv \theta_h + \theta_s) = \Pi_s^*(\theta_s) + \Pi_h^*(\theta_h)$, then $\Pi_i^*(\theta_i) > \Pi_j^*(\theta_j)$ where $j = s, h$ and hence

$$\Pi_i^*(\theta_i) = Max\{\Pi_s^*(\theta_s), \Pi_h^*(\theta_h), \Pi_i^*(\theta_i), 0\}.$$

To see the converse, let $\Pi_i^*(\theta_i) = Max\{\Pi_s^*(\theta_s), \Pi_h^*(\theta_h), \Pi_i^*(\theta_i), 0\}$. Since $\Pi_i^* = \Pi_s^* + \Pi_h^*$ then $\Pi_s^* + \Pi_h^* > 0$. For the sum to be greater than zero, three cases exist: (a) $\Pi_h^* > 0$ and $\Pi_s^* > 0$. This implies $\theta_h < \theta_h^c$ and $\theta_s < \theta_s^c$. The other two cases are (b) $\Pi_h^* > 0$ and $\Pi_s^* < 0$, i.e., $\theta_h < \theta_h^c$ and $\theta_s > \theta_s^c$ and (c) $\Pi_h^* < 0$ and $\Pi_s^* > 0$, i.e., $\theta_h > \theta_h^c$ and $\theta_s < \theta_s^c$. However, since $\Pi_i^* = \Pi_s^* + \Pi_h^*$, both (b) and (c) contradict the assumption $\Pi_i^*(\theta_i) = Max\{.,.,., 0\}$. For instance, if (b) is true, then $Max\{.,.,., 0\} = \Pi_h^*$ while if (c) is true then $Max\{.,.,.,0\} = \Pi_s^*$. Proof of statement (2) is similar. □

Proof of Proposition 4.4. Let η be relative odds of closed firm entry (relative to open firm entry). Then, per proposition 4.2,

$$\eta = \frac{F_s(\theta_s^c)F_h(\theta_h^c)}{F_h(\theta_h^c)\{1 - F_s(\theta_s^c)\} + F_s(\theta_s^c)\{1 - F_h(\theta_h^c)\}}.$$

Observe that the relative odds are less than one whenever $F_h(\theta_h^c) < \frac{F_s(\theta_s^c)}{3F_s(\theta_s^c)-1}$ if $F_s(\theta_s^c) > 1/2$ and $F_h(\theta_h^c) \in (0, 1)$ if $F_s(\theta_s^c) < 1/2$. Suppressing the argument θ_s^c and θ_h^c where obvious, then $\eta < 1$ is true over the set given by $\Phi = \Phi_1 \cup \Phi_2$ where $\Phi_1 = \{(F_s(.), F_h(.)) : F_s(.) \leq 1/2\}$ and $\Phi_2 = \{(F_s(.), F_h(.)) : F_s(.) > 1/2, F_h(.) < F_s(.)/(3F_s - 1)\}$ (see Figure 6, top right panel). Since $F_s(.)$ and $F_h(.)$ are both CDFs of two continuous random variables, hence the functions $F_s^{-1}(.)$ and $F_h^{-1}(.)$ exist. Let $\Theta \subset \theta_s \times \theta_h$ such that $\Theta = \Theta_1 \cup \Theta_2$ where $\Theta_1 = \{(\theta_s^c, \theta_h^c) : \theta_s^c \leq F_s^{-1}(1/2)\}$ and $\Theta_2 = \{(\theta_s^c, \theta_h^c) : \theta_s^c > F_s^{-1}(1/2), \theta_h^c < F_h^{-1}(\frac{F_s(\theta_s^c)}{3F_s(\theta_s^c)-1})\}$ (see Figure 6, bottom right panel).

Then there exists a function $G : F_s \times F_h \to \theta_s \times \theta_h$ such that for any $\theta \in \Theta$, $G^{-1}(\theta) \in \Phi$. Specifically, define $G(\phi)$ for any $\phi = (\phi_s, \phi_h) \in F_s \times F_h$ as $G(\phi) = (G_s(\phi_s, \phi_h), G_h(\phi_s, \phi_h)) = (F_s^{-1}(\phi_s), F_h^{-1}(\phi_h))$. It is easy to verify that every element of Θ is mapped to a point in the set Φ via the function G^{-1}

To see this, let $\theta = (\theta_s^c, \theta_h^c)$ be an arbitrary point in Θ. Then θ is either in Θ_1 or in Θ_2. Assume that $\theta \in \Theta_1$. Then $G^{-1}(\theta) = (F_s(\theta_s^c), F_h(\theta_h^c))$. But since $\theta \in \Theta_1$, then it must be that $\theta_s^c \leq F^{-1}(1/2)$ and since $F_s(.)$ is monotonic therefore $F_s(\theta_s) \leq 1/2$. But then this implies that $G^{-1}(\theta) \in \Phi_1$. Alternatively if $\theta \in \Theta_2$ then it must be that $\theta_s^c > F^{-1}(1/2)$ and $\theta_h^c < F_h^{-1}(\frac{F_s(\theta_s^c)}{3F_s(\theta_s^c)-1})$ and so again by the monotonicity of $F_s(.)$ and $F_h(.)$, we have that $F_s(\theta_s^c) > 1/2$ and $F_h(\theta_h) < \frac{F_s(\theta_s^c)}{3F_s(\theta_s^c)-1}$. This is

[16] When $\frac{\theta_h}{\theta_s} = \frac{p_q - p_s}{p_s}$, $q_s = q_h = q_i$, so that $\Pi_s^*(\theta_s, \text{q}(\theta_i)) = \Pi_s^*(\theta_s)$ and $\Pi_h^*(\theta_h, \text{q}(\theta_i)) = \Pi_h^*(\theta_h)$.

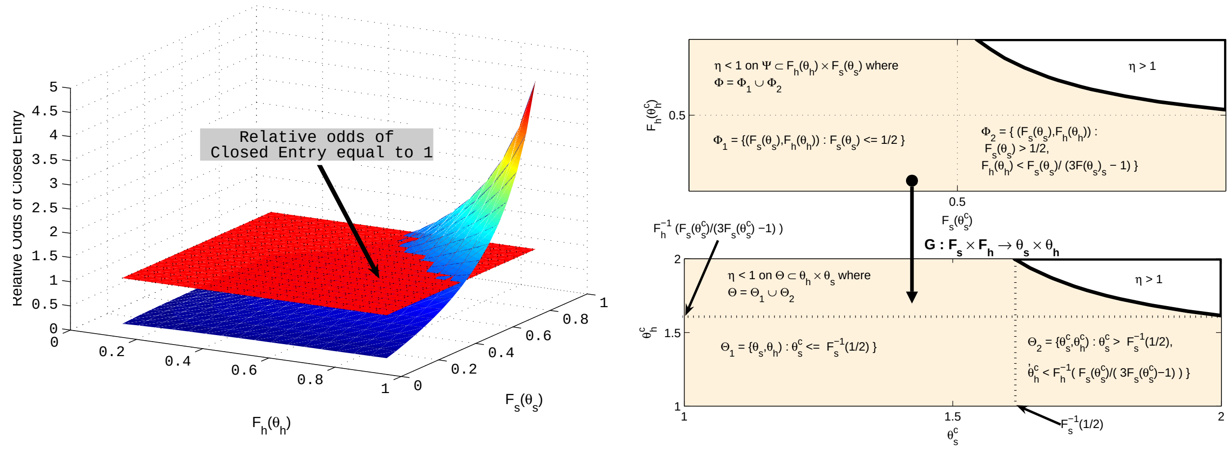

FIGURE 6. Relative Odds of Closed Entry

turn means that $G^{-1}(\theta) \in \Phi_2$. Thus every element of Θ is mapped to a point in the set Φ via the function G^{-1}.

This establishes that for all points in the set Θ, the relative odds of closed firm entry are less than one. □

Proof of Proposition 4.5. Observer that the relative odds of closed entry given in the last proposition are monotonic in both $F_s(\theta_s^c)$ and $F_h(\theta_h^c)$ (see also Figure 6, left panel). Further, $F_s(\theta_s^c)$ and $F_h(\theta_h^c)$ are monotonic in θ_s^c and θ_h^c respectively and these in turn are monotonic functions of prices p_h and p_s (see Equations [8]). Hence the relative odds of closed entry are monotonic in prices. □

Proof of Proposition 4.6. First observe that $\theta_h^c = \theta_s^c$ if and only if $p_h = p_s$ for non-negative real prices (see equations 8 and recall that $p_h \equiv p_q - p_s$). Further, $p_h = p_s$ implies $p_q = 2p_s$. Inspection of equations 6b shows that if either $n_s \neq n_h$ or $\sum(1/\theta_s) \neq \sum(1/\theta_h)$, then $p_q \neq 2p_s$. Hence, $\theta_h^c \neq \theta_s^c$. This proves the first statement. The proof for the second part is as follows: First observe that if F'/F is monotone decreasing, then $\frac{FF''-F'^2}{F^2} < 0$, or simply $FF'' < F'^2$. Next, let $\theta_s^c + \theta_h^c = \rho$ and let $\theta_s^c - \theta_h^c = \epsilon$. Then observe that if $\epsilon = 0$ then $\theta_h^c = \theta_s^c = \rho/2$ and if $\epsilon \neq 0$ then $\theta_s^c = (\rho+\epsilon)/2$ and $\theta_h^c = (\rho-\epsilon)/2$. Thus,

$$Pr\big(\text{I-type enters}|\ \theta_s^c = \theta_h^c, \theta_s^c + \theta_h^c = \rho\big) = F(\theta_s^c).F(\theta_h^c) = F(\rho/2).F(\rho/2)$$

and similarly

$$Pr\big(\text{I-type enters}|\ \theta_s^c \neq \theta_h^c, \theta_s^c + \theta_h^c = \rho\big) = F(\theta_s^c).F(\theta_h^c) = F((\rho+\epsilon)/2).F((\rho-\epsilon)/2).$$

Let $G(.)$ be the second of these probabilities. Then, it suffices to show that $G(.)$ is maximized at $\epsilon = 0$. It can be easily verified that $\partial_\epsilon G = 0$ at $\epsilon = 0$. Further, the second order condition for G to be a local max at $\epsilon = 0$, (i.e. for $\partial^2_{\epsilon\epsilon} G < 0$) is that $F.F'' < F'^2$. This condition can be re-written as $F''/F' < F'/F$. But this is precisely the condition which is true if F'/F is monotone decreasing. □

APPENDIX 2

For the base line simulations, parameter values used in the simulations are $\alpha = \beta = 1, a = 40, b = -1$. Starting number of firms were 20 closed firm equivalents. A pair of H and S type firms is treated as equivalent to one closed firm.

Simulation Design: Separate simulations were run for various values of γ and τ. Specifically, we varied (γ - 2τ)/τ between -2 and 2 in increments of 0.2. For all simulations, we fixed the value of τ at 0.25 and set the value of γ between 0 and 1 so that $(\gamma - 2\tau)/\tau$ is between -2 and 2. Thus $(\gamma - 2\tau/\tau) = -2$ corresponds to the case when γ is 0% of the fixed costs incurred by a closed firm and $(\gamma - 2\tau/\tau) = +2$ corresponds to the case when γ is 50% of the fixed costs of a closed firm. At the average values of τ and γ, the long run average cost are about 6.47, and the total cost per firm are about 7.24. This implies that the total fixed costs for the open firm = $\alpha + \beta + 2\tau = 2.5$, or about 34.5% of the total cost. Thus our simulations imply that the fixed costs of the closed firm ranges between 2 and 3. Put differently, the variation is a little less than 15% of total cost.

For each value of (γ - 2τ)/τ, we ran thirty five simulations. All the variables and initial conditions were the same across each set of 35 simulations, except for the seed used to generate the random numbers *within* a simulation, which was different. Thus, a total of 35×21 = 735 simulations was run with the initial number of firms chosen such that the initial degree of vertical integration was about 0.5. In addition, we also ran some simulations with the initial conditions such that the market share of closed firms in the first period was about 0.2 or 0.8. For both low and high initial value of MS, (γ - 2τ)/τ was set at -2, 0 and 2 (thus the additional simulations were, $35 \times 3 \times 2 = 210$).[17] All simulations were run for 500 iterations (periods).

Algorithm (for Simulations).

(1) Period 1:
   (a) Set initial number of firms of each type.
   (b) Given the number of firms of each type, generate as many random numbers between appropriate ranges for the efficiency parameters.
   (c) Use Equations (4a,4b,4c) to compute the output of each firm. If the output of any firm is negative, delete that firm.
   (d) Given the parameters of the demand curve (slope and intercept) use equations (6a,6b) to compute market prices.
   (e) Given market prices, compute the profits of each firm. If firms have profits less than zero, then delete the firm with the most negative profit. Recompute prices and profits. Repeat, until all firms have non-negative profit. At this point, record the total outputs, number of firms of each type, prices, market share of closed firms and other variables of interest, as the first period values.

(2) Period t:
   (a) Generate two random numbers between 1 and 2.
   (b) Given the prices at the end of the t -1 period and the two random numbers generated, compute potential outputs and potential profits for H-type, S-type and I-type (where the potential profits for I-type are computed using the sum of the two random numbers just generated). An entry is marked (i.e., the number of firms of j-type increase by

[17] All in all, we actually ran over 2000 simulations where we also changed other parameters, such as (1) demand curve parameters, (2) support for distribution of random numbers, and (3) by allowing τ to be changed endogenously (with various specifications for endogeneity). These additional simulations, not reported in the paper, had similar results.

one) if the potential output is non-negative and the potential profit is maximum and non-negative.

(c) If entry takes place, recompute the prices (6a,6b) outputs (4a,4b,4c) and profits of all existing firms.

(d) If firms have negative outputs or negative profits, they exit (i.e. are deleted) sequentially. The firm making the most negative profit exits first. Prices, outputs and profits of all remaining firms are recomputed. The process is repeated until none of the incumbents have negative outputs or profits. At this point, record the total outputs, prices, number of firms of each type, market share of closed firms and other variables of interest, as the **t** period values.

REFERENCES

ADAMS, W. J., AND J. L. YELLEN (1976): "Commodity bundling and the burden of monopoly," *Quarterly Journal of Economics*, 90(3), 475–498.

DENICOLO, V. (2000): "Compatibility and bundling with generalist and specialist firms," *The Journal of Industrial Economics*, 48(2), 177–188.

ECONOMIDES, N. (1989): "Desirability of compatibility in the absence of network externalities," *American Economic Review*, 79, 11651181.

FARRELL, J., H. K. MONROE, AND G. SALONER (1998): "The vertical organization of industry: Systems competition versus component competition," *Journal of Economics and Management Strategy*, 7(2), 143–182.

FARRELL, J., AND G. SALONER (1985): "Standardization, compatibility and innovation.," *RAND Journal of Economics*, 16, 70–83.

——— (1986): "Standardization and variety," *Ecnomic Letters*, 20, 71–74.

JOVANOVIC, B. (1982): "Selection and the evolution of industry," *Econometrica*, 50(3), 649–670.

KLEPPER, S. (1996): "Entry, exit, growth, and innovation over the product life cycle," *American Economic Review*, 86(3), 562–583.

LAFONT, J., AND J. TIROLE (1988): "Dynamics of incentive contracts," *Econometrica*, 59, 1735–1754.

LANGLOIS, R. N. (1992): "External economies and economic progress: The case of the microcomputer industry," *Business History Review*, 66, 1–50.

MATUTES, C., AND P. REGIBEAU (1988): "Mix and Match: Product compatibility without network externalities," *RAND Journal of Economics*, 19, 221–234.

——— (1992): "Compatibility and bundling of complementary goods in a duopoly," *The Journal of Industrial Economics*, 40(1), 37–54.

MYERSON, R., AND M. SATTERTHWAITE (1983): "Efficient mechanisms for bilateral trading," *Journal of Economic Theory*, 28, 265–281.

PORTER, M. E. (1980): *Competitive strategy: Techniques for analyzing industries and competitors*. Free Press, New York.

ROSENBERG, N. (1994): "Charles Babbage: Pioneer economist," in *Exploring the Black Box*, chap. 2, pp. 24–46. Cambridge University Press, New York.

SCHMALENSEE, R. (1984): "Gaussian demand and commodity bundling," *Journal of Business*, 57(1), S211–S230.

STIGLER, G. J. (1951): "The division of labor is limited by the extent of the market," *Journal of Political Economy*, 59(3), 185–193.

WHINSTON, M. D. (1990): "Tying, foreclosure, and exclusion," *American Economic Review*, 80(4), 837–860.