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Abstract

This paper uncovers a novel pattern of offshoring and market structure in a high-tech industry, and proposes a simple oligopoly model to explain it. Specifically, the hard disk drive industry (1976–98) witnessed massive waves of entry, exit, and the relocation of manufacturing plants to low-cost countries, in which shakeouts occurred predominantly among home firms and almost all survivors were offshore firms. I build and estimate a dynamic offshoring game with entry/exit to explain these facts, and then investigate the relationship between offshoring and market structure as well as the impacts of hypothetical government interventions.

Keywords: Dynamic Oligopoly, Industry Life Cycle, Offshoring, Strategic Trade Policy

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1 Introduction

This paper empirically investigates high-tech firms’ decisions to relocate manufacturing plants to low-cost countries: offshoring.¹ Computers and electronics industries have undergone sector-wide offshoring and typically feature an oligopolistic market structure of a global scope.² Contrary to the standard models of international trade and offshoring with monopolistic competition, oligopoly settings imply a firm’s profit and survival depend not only on the firm’s own production location (and hence cost structure), but also on its rivals’ locations. Thus its incentives to offshore and its prospect of survival will depend on its rivals’ offshoring decisions as well, giving rise to an environment in which offshoring becomes a strategic, forward-looking decision. This paper studies strategic industry dynamics of offshoring.

The purpose of this paper is three-fold. First, it aims to explore and describe the patterns of offshoring and firm survival, using unique data on hard disk drive (HDD) manufacturers (1976–98). Second, I construct and estimate a simple model of industry dynamics to explain the data patterns and disentangle the empirical relationship between offshoring and competition. Third, I assess the implications of government interventions to help or hinder domestic firms’ offshoring activities. The research questions underlying these analytical goals ask how competition (market structure, including rivals’ locations) affects offshoring incentives, and in turn, how the possibility of offshoring affects market structure in the long run. These questions are important because the economic forces of global competition determine the life and death of firms, and sometimes of an entire domestic industry.

Three sets of findings emerge. First, the descriptive analysis uncovers a novel pattern of offshoring and market structure: (1) the number of firms grew in the first half of the sample and then declined in the second half,³ in a typical Klepper-style shakeout; (2) the fraction of firms that switched to offshore production monotonically increased throughout the sample

¹I define offshoring as a change in firms’ production locations from North to South *within* their organizational boundaries (i.e., foreign direct investment in their *own* manufacturing plants). A broader definition of offshoring would also include “outsourcing” of tasks to foreign firms, but I focus on the “narrower” classification (Feenstra 2010) because of the latter’s importance in my data.

²The computers and electronics sector has experienced the largest offshoring-related change in U.S. jobs between 2000 and 2010, followed by textiles and clothing, and chemicals and plastics. See *The Economist*, “Special Report: Outsourcing and Offshoring,” January 19, 2013.

³Most of the exits throughout my sample period (1976–98) were due to bankruptcy and liquidation. By contrast, almost all exits since 2000 were through mergers. See Igami and Uetake (2014) for the analysis of shakeout with mergers during the latter period.

period; and (3) the shakeout occurred predominantly among home firms, to the extent that almost all survivors were offshore firms at the end of the sample period. Second, a simple dynamic oligopoly model fits these patterns surprisingly well, and the estimates suggest that because of competitive pressure, the incentives to offshore increase as more rivals offshore: offshoring breeds offshoring. Third, my counterfactual simulations show that (1) offshoring is pro-competitive, (2) discouraging offshoring would risk the survival of domestic firms, and (3) governments in Nash equilibrium would engage in either a subsidy race to drive out foreign firms, or free-riding on foreign firms' offshoring efforts, depending on policy objectives (i.e., to maximize domestic producer surplus or national welfare).

The intuition behind the finding that offshoring breeds offshoring is as follows. Offshore firms produce HDDs at lower marginal costs than home firms, thereby putting downward pressure on the global HDD price and stealing market shares from the latter. Thus, offshoring represents a cost-reducing investment of strategic nature, and this competitive pressure leads the remaining home firms to choose between exiting and offshoring. Explained in this manner, the mechanism might appear obvious and straightforward, but it does not automatically follow from my modeling assumptions (in particular, that of Cournot oligopoly in period competition). In fact, one would expect the opposite result from a Cournot model, wherein outputs are strategic substitutes, and hence the incremental profit from a cost-reducing investment decreases as a firm faces an increasing number of low-cost rivals. However, this static prediction of strategic substitutability may be reversed once we allow for the endogenous evolution of market structure in a fully dynamic environment, as I will illustrate using a stylized Cournot example in section 3. In general, the relationship between market structure and the incentives to offshore will depend on the price elasticity of demand, the extent of marginal-cost reduction by offshoring, the sunk cost of offshoring, as well as the firm's expectation about the evolution of future market structure; hence every piece of the empirical analysis (which I will describe in the following) counts toward my finding.

I have chosen to study the HDD market because it epitomizes high-tech sectors that underwent massive waves of offshoring in the last half century. My data set consists of two parts. The first part records the industry-average price and aggregate shipment quantity of HDDs. The second part is a panel of the world's HDD manufacturers that contains information on their entry, exit, production locations (i.e., whether their plants are in the North or the South), as well as market shares.

I use these data along with a simple structural model to replicate and explain the salient patterns of offshoring and competition, and to disentangle their empirical relationship, in three steps. First, the data on the aggregate price and quantity allow me to estimate the elasticity of the HDD demand. Second, I motivate and assume Cournot competition with heterogeneous costs (locations) in the period competition, the first-order conditions of which imply the marginal costs of producing HDDs in the North and the South in each year. The difference in marginal costs represents the benefit from offshoring, and the intuition for its identification is straightforward: the greater the observed market shares of offshore firms relative to home firms, the lower the implied marginal cost of production in the South relative to the North. These static demand and cost estimates permit the calculation of the period profits for both home and offshore firms in each year, in any market structure. In the third step, I embed these implied period profits into a dynamic oligopoly game of entry, exit, and offshoring to incorporate the endogenous evolution of market structure, which serves as a backbone of my unified framework to explain the key facts about the industry dynamics of offshoring. For each candidate vector of parameters (i.e., the fixed and sunk costs), I solve this dynamic game for a Perfect Bayesian Equilibrium (PBE) by backward induction, construct the likelihood of observing the actual choices in the data, and obtain as the maximum likelihood estimate the parameter vector that best rationalizes the observed patterns of entry, exit, and offshoring. The estimated policy function (i.e., the optimal choice probability of offshoring as a function of market structure) reveals the equilibrium relationship between competition and offshoring.

I then, in three different settings, assess the welfare implications of government interventions by counterfactual simulations in which the sunk cost of offshoring is altered, either exogenously or as a public-policy instrument. First, eliminating the possibility of offshoring (e.g., no free trade with Singapore, which hosted most of the offshore HDD plants) would harm consumers because of higher costs but would make the survival of home firms easier. Thus, offshoring is pro-competitive and plays the role of “drastic” innovation in Arrow’s (1962) sense; that is, it alters market structure along with the industry’s cost structure. Second, given the public’s and politicians’ hostility toward “shipping jobs overseas,” I consider a unilateral intervention by the U.S. government to discourage offshoring. In this case, American firms would be stuck in the high-cost location at home, whereas foreign firms (e.g., from Japan and the U.K.) would continue offshoring and eventually drive American

firms out of the global HDD market in the long run. Thus seemingly “protectionist” policies may actually destroy the domestic industry: If you can’t beat them, join them. Third, I examine the Nash equilibrium outcomes of government interventions in which two Northern governments change the effective costs of offshoring to promote “national interests,” in the spirit of strategic trade policies. If the governments seek to maximize their respective national producer surplus, they will subsidize offshoring in the hope of driving out foreign firms: a mercantilist case. By contrast, if the governments seek to maximize their respective national welfare (net of government revenue/expenditure), they will “tax” offshoring to avoid sunk costs. Because the product market is global, the world’s consumers can benefit from the low-cost production by any firms regardless of nationality. Thus the governments would rather free-ride on foreign firms’ offshoring (cost-reduction) efforts to satisfy domestic consumers. These counterfactual experiments illustrate the benefits and costs of government interventions, as well as the implications of different levels of international trade/investment costs.

This paper proceeds as follows. Section 1.1 discusses how this paper relates to the existing literature. Section 2 explores the patterns of entry, exit, and offshoring in the HDD industry and presents preliminary data analysis (with supplementary tables and figures in Appendix A.1). Section 3 starts with a static Cournot example to facilitate an intuitive understanding of the relationship between competition and offshoring, and then develops a fully dynamic model. Sections 4 and 5 explain the estimation procedure and results, including the fit and the equilibrium competition-offshoring relationship in the estimated policy function (with robustness checks in Appendix A.2). Section 6 investigates the implications of higher trade/investment costs and government interventions. Section 7 concludes.

1.1 Related Literature

This paper empirically investigates firms’ incentives to offshore, and focuses on the potential advantage of offshoring in global competition. By contrast, the existing literature on offshoring has mostly focused on labor-market outcomes (e.g., job destruction) at the aggregate level.⁴ More specifically, I study the strategic industry dynamics of offshoring and

⁴Feenstra and Hanson (1996, 1997, 1999, 2003), Autor, Levy, and Murnane (2003), Hsieh and Woo (2005), Feenstra (2010), Ottaviano, Peri, and Wright (2010), Burstein and Vogel (2011), Acemoglu, Gancia, and Zilibotti (2012), and Pierce and Schott (2012).

build on three strands of literature, namely, industrial organization (IO), trade, and industry dynamics.

First, I model the firms' offshoring as a discrete investment decision to reduce future production costs. Methodologically, the most closely related papers are Benkard (2004), Schmidt-Dengler (2006), Goettler and Gordon (2011), Lee (2013), and Igami (2014), each of which estimates a dynamic oligopoly game of investment using a full-solution approach.⁵ I extend the scope of such analysis to the context of globalization.

Second, the empirical trade literature has investigated the firm's trade and investment decisions, a form of which is offshoring. Specifically, Das, Roberts, and Tybout (2007), Xu (2008), and Aw, Roberts, and Xu (2009) estimate structural models of export dynamics, in the trade tradition of monopolistic competition frameworks.⁶ By contrast, this paper analyzes offshoring dynamics in a strategic environment, which materially complicates the analysis but contributes novel insights in terms of both empirical findings (e.g., offshoring breeds offshoring because of competitive pressure) and policy implications (e.g., if you can't beat them, join them), some of which resonate with the earlier literature on strategic trade policies.⁷

Third, the industry dynamics literature has uncovered empirical regularities in the life cycle of industries. In particular, shakeout (i.e., mass exits of firms in a maturing industry) is a common phenomenon in the emergence of oligopolistic industries.⁸ The models of Jovanovic and MacDonald (1994) and Hopenhayn (1993) highlight the role of cost-reducing investments (process innovations) in shakeouts. Sutton (1991, 1998, 2013) suggests globalization and rising sunk costs can explain increasing concentration of market shares in many industries. This paper presents new empirical evidence that offshoring has played the role of "drastic"

⁵See Igami (2014) for the methodological considerations in estimating a dynamic oligopoly model with data from a global, innovative industry.

⁶Theoretical work on offshoring includes Acemoglu, Gancia, and Zilibotti (2012), Baldwin and Venables (2012), Grossman and Rossi-Hansberg (2008), Antràs, Garicano, and Rossi-Hansberg (2006), Grossman, Helpman, and Szeidl (2005), and Antràs and Helpman (2004). Some implications of these models have been tested empirically, such as the productivity-based sorting patterns of firms, in Bernard, Jensen, and Schott (2009), and Eaton, Kortum, and Kramarz (2004).

⁷Theoretical inquiries into trade policy have analyzed the strategic uses and welfare implications of tariffs, anti-dumping, quotas, and subsidies (e.g., Brander and Spencer 1985, Eaton and Grossman 1986, Helpman and Krugman 1989, Bagwell and Staiger 1990, Grossman 1994). Corresponding empirical works have measured and evaluated the actual effects of these trade policies (e.g., Berry, Levinsohn, and Pakes 1995, 1999; Feenstra and Levinsohn 1995; Goldberg 1995).

⁸See Gort and Klepper (1982), Klepper and Graddy (1990), and Utterback and Suárez (1993) for the stylized facts about shakeout. See Hünermund, Schmidt-Dengler, and Takahashi (2014) for a structural analysis of oligopolistic shakeouts.

innovation (Arrow 1962) in accelerating shakeout in the high-tech industry, and illustrates the process of creative destruction from a global perspective.

2 Data Patterns

This section portrays the data patterns of offshoring in the HDD industry. First, I summarize key facts about the growing importance of offshoring in HDD production due to its cost advantage. Second, I conduct a preliminary data analysis to gain insights into who offshores and when. These data patterns will motivate my analytical focus on market structure dynamics and the modeling of home and offshore production with heterogeneous marginal costs in the next section.

2.1 Offshoring in the HDD Industry

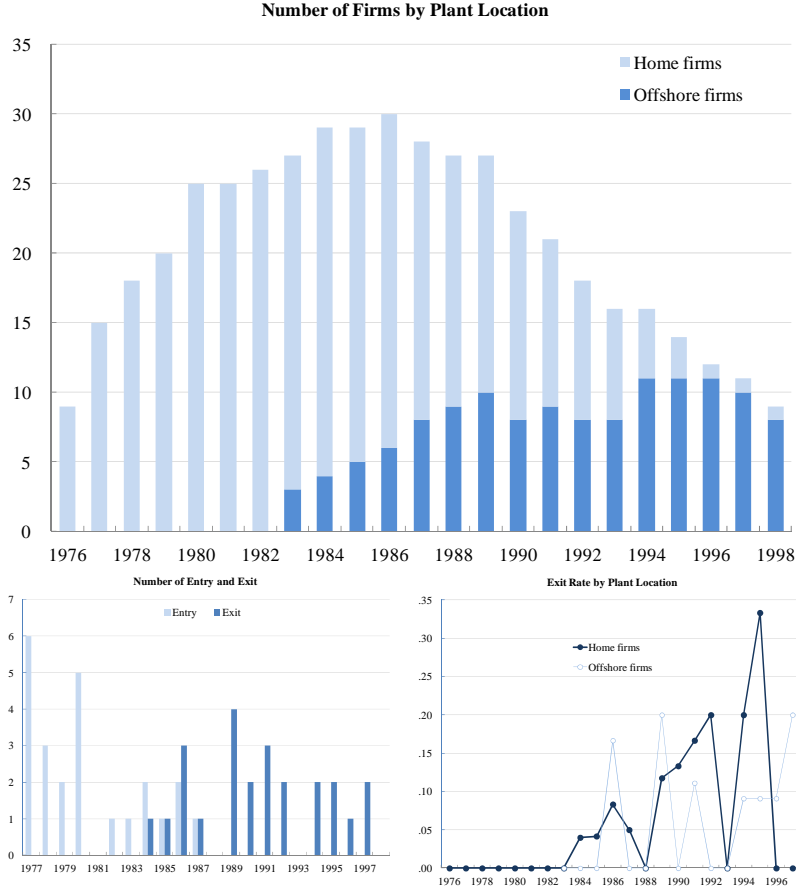
Long before economists started using the words “offshoring” and “globalization,” firms from rich countries built factories in developing countries to reduce production costs.⁹ As early as 1961, Singapore established the Economic Development Board, a one-stop government agency to help multi-national corporations’ (MNCs) foreign direct investment (FDI), which subsequently succeeded in persuading electronics firms such as Texas Instruments, Hewlett-Packard, and General Electric to set up plants in the country. These American MNCs laid the foundations for Singapore’s high-tech manufacturing during the 1970s (Lee 2000).

The HDD industry witnessed the growing importance of offshore production during the 1980s and 1990s. All major HDD makers were headquartered and started production in the North (mostly in California), but some of them moved their manufacturing plants to Singapore and its neighboring countries in South-East Asia. Figure 1 shows that all but one surviving firm became offshore producers by 1996. The industry source suggests over 90% of the world’s HDDs were processed in Singapore, so my formal analysis in the subsequent sections will model Singapore and its neighboring countries as a single offshore location.¹⁰ Likewise, the baseline model will treat all Northern locations symmetrically, but I will allow

⁹General Accounting Office, “Offshoring: U.S. Semiconductor and Software Industries Increasingly Produce in China and India,” September 2006.

¹⁰Malaysia and Thailand functioned as hinterlands, to which simpler production processes were further offshored from Singapore, according to McKendrick, Doner, and Haggard’s (2000) case studies. The Philippines hosted a few Japanese HDD makers. Toward the end of the 1990s, the Chinese cities of Hong Kong, Shenzhen, and Harbin also started to attract HDD production, but Singapore continued to be the hub of these global supply chains.

Figure 1: Evolution of Market Structure and Offshoring in the HDD Industry

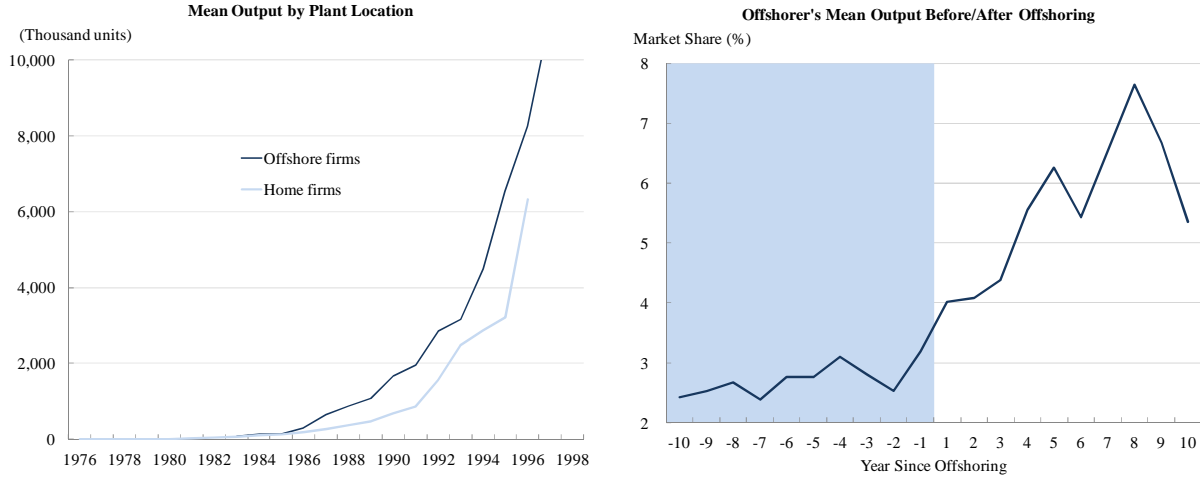


Note: Major firms (with market shares greater than 1% of the global HDD output) only.

for heterogeneous offshoring costs by country when conducting strategic offshoring policy counterfactuals in section 6. The figure also shows the period of increasing offshoring coincided with the end of massive entry and the onset of shakeout, which happened predominantly among home firms. Thus we can describe these patterns as classical Klepper-style mass entry and exit in the life cycle of an industry, but on a global scale with the new dimension of offshoring, in which shakeout happens disproportionately among those firms that stayed in home locations. These patterns are the salient features of industry dynamics that I seek to model and explain.

Why did these firms move their plants to Singapore? Disentangling the relationship between offshoring and competition (including market structure dynamics with entry and exit) is a complicated task and the focus of my structural analysis in the subsequent sections, but the basic reason for offshoring is simple. Seagate Technology, a leading HDD maker, relocated its entire assembly from Scotts Valley, California, to Singapore because of the “high

Figure 2: More Production after Offshoring



Note: The left panel plots the average firm's output by manufacturing location. The right panel focuses on those firms that offshored eventually, and plots the average market share in terms of analysis time before/after offshoring.

cost, marginal quality and poor availability of labor” in the home location.¹¹ Singapore was not necessarily the cheapest place to hire manufacturing workers, and its neighbors such as Malaysia and Thailand offered lower wage rates during the sample period (see Appendix A.1.1). But the quality-adjusted availability of labor in Singapore was the most attractive of the region, along with its market-friendly government, open trade policy, tax incentives, and reliable infrastructure. By the mid 1980s, Singapore had built a reputation and track record of hosting various computer and electronics industries from abroad, so the city state had accumulated a sizable pool of managers, engineers, technicians, and operators with relevant skills from inside and outside its national borders.¹²

The advantage of offshore production is evident in the market-share data. Figure 2 (left) suggests an average offshore firm sold more than twice as many HDDs as an average home firm in most years, because of lower marginal costs of production. In principle, such a gap in productivity can arise solely on the basis of more productive firms self-selecting into offshore locations, that is, even if Singapore offered no cost advantage. However, Figure 2 (right) shows the relative size of offshore firms started to grow *after* offshoring. A further

¹¹See McKendrick, Doner, and Haggard (2000). A co-founder of Seagate reportedly summarized the situation as follows: “We had too many surfers.”

¹²At the macroeconomic level, the steady inflow of foreign direct investment and the increased demand for labor from those foreign firms must have contributed to the rise in wages in Singapore over several decades, and hence the labor-market conditions were endogenous outcomes of offshoring in many industries. The analysis of such general-equilibrium effects are outside the scope of this paper because of my focus on the dynamics of a single industry, the trajectory of which was unlikely to have altered macroeconomic patterns.

data exploration (Appendix A.1.2) finds little evidence of persistent productivity differences or productivity-based sorting of firms into offshoring. This (lack of a) finding does not necessarily rule out the possibility of sorting along some other unobservable dimensions,¹³ but because no clear patterns emerged in this respect, my subsequent analysis will focus on the modeling and estimation of heterogeneous production costs between home and offshore locations. Given the large differences in wage rates between Singapore and the United States (Appendix A.1.1), I believe they are likely to affect market shares and firm survival with first-order magnitude.

Table 1: Descriptive Statistics of 151 HDD Makers

Variable	Num. of obs.	Mean	Std. dev.	Minimum	Maximum
Mean revenue from HDD sales	151	103.7	650.7	0	7764.8
First year in HDD market	151	1982.9	5.4	1976	1998
First year of offshoring	42	1988.9	4.3	1983	1998
Initial tech generation of entry					
Indicator: <i>14 inch</i>	151	.23	.42	0	1
Indicator: <i>8 inch</i>	151	.10	.30	0	1
Indicator: <i>5.25 inch</i>	151	.39	.49	0	1
Indicator: <i>3.5 inch</i>	151	.24	.43	0	1
Indicator: <i>2.5 inch</i>	151	.04	.20	0	1
Organizational type					
Indicator: <i>Specialized HDD maker</i>	151	.42	.49	0	1
Indicator: <i>Computer maker</i>	151	.30	.46	0	1
Indicator: <i>HDD component maker</i>	151	.07	.26	0	1
Indicator: <i>Other electronics maker</i>	151	.21	.41	0	1

Note: Major and fringe firms in the mainstream segment (non-captive, fixed HDDs).

2.2 Who Offshores and When?

The original data source, *DISK/TREND Reports*, contains 1,378 annual records for 178 firms between 1976 and 1998, of which 151 firms were active in the mainstream segment (the non-captive market for fixed HDDs). Table 1 summarizes the characteristics of these 151 firms, of which 42 switched to offshore production at some point. Structural analysis in the subsequent sections will focus on major firms whose global market shares surpassed 1%, whereas the descriptive analysis in this section incorporates fringe firms as well, for the sake of completeness.

¹³Appendix A.2.2 features the estimation of an augmented model with organizational heterogeneity, an observed firm characteristic, because the preliminary regressions in the next subsection suggests this attribute as a good predictor of offshoring.

Table 2: Preliminary Regression of Offshoring Timing on Firm Characteristics

Dependent variable: <i>Decision to Offshore</i>	Duration model (Cox proportional hazard; <i>the baseline coefficient = 1</i>)							
	(1)	(2)	(3)	(4)				
Firm size _{it}	1.000	(.000)	—	(—)	—	(—)	1.000	(.000)
HDD entry year _i	—	(—)	1.062*	(.033)	—	(—)	.935	(.083)
% offshore firms _t	—	(—)	—	(—)	14.83***	(14.85)	21.29	(48.52)
Initial tech generation								
8-inch	—	(—)	—	(—)	—	(—)	1.531	(1.084)
5.25-inch	—	(—)	—	(—)	—	(—)	2.204	(1.468)
3.5-inch	—	(—)	—	(—)	—	(—)	1.973	(1.511)
2.5-inch	—	(—)	—	(—)	—	(—)	3.873	(3.748)
Organizational type								
Specialized HDD maker	—	(—)	—	(—)	—	(—)	5.705***	(3.235)
Computer maker	—	(—)	—	(—)	—	(—)	1.911	(1.189)
HDD component maker	—	(—)	—	(—)	—	(—)	1.218	(1.388)
Number of firms	151	151	151	151				
Number of offshoring	42	42	42	42				
Time at risk	772	772	772	772				
Log likelihood	−181.84	−180.53	−179.57	−169.20				

Note: Coefficients greater (less) than 1 indicate higher (lower) propensities to offshore. Firm size is measured by its revenue from HDD sales. % offshore firms measures the fraction of offshore firms in the global market. Omitted categories are “14-inch” and “Other electronics maker.” ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Standard errors in parentheses.

As a preliminary, descriptive analysis, I regress the timing of offshoring (i.e., each firm’s year of initial production of HDDs in Singapore and its neighbors) on firm characteristics, as well as the fraction of firms in the industry that have already offshored. Table 2 reports the results based on a standard duration model (Cox proportional hazard estimates, wherein *1 is the baseline coefficient level*), which suggests five patterns (or lack thereof). First, *the firm’s HDD sales*, a proxy for size and productivity, do not appear to correlate with its propensity to offshore. Firm size is so volatile in high-tech industries that one cannot interpret it as a measure of persistent heterogeneity (see Appendix A.1.2 for details). Second, *the firm’s year of entry* into the HDD market, a (negative) proxy for age, correlates positively with offshoring, suggesting younger firms tend to be more footloose. When the firm’s initial technological generation (smaller diameters represent newer products) is added, however, the relationship ceases to be measurable. Third, *the fraction of offshore firms* in the industry is a strong predictor of offshoring propensities of the remaining home firms, although its statistical significance drops when we add a full set of firm characteristics. Fourth, *the firm’s initial technological generation* (and hence its product portfolio) does not appear to correlate with offshoring in any systematic manners.

Fifth, *specialized manufacturers of HDDs* are three to six times more likely to offshore than the other types of firms (either vertically integrated or horizontally diversified), presumably because the latter types of firms have to consider joint-location problems of multiple divisions. To my knowledge, the existing literature has not predicted or discovered this relationship, but this organizational aspect of firm heterogeneity appears to correlate strongly with offshoring decisions.

This exploratory data analysis treats each firm as an independent decision maker (as in monopolistic competition models) and therefore does not incorporate the endogenous evolution of market structure due to entry, exit, and offshoring. Hence we cannot necessarily conclude much from these estimates, but these patterns are useful for modeling choices. The solution and estimation of a dynamic oligopoly game are computationally expensive, so one has to decide where to focus modeling efforts. My baseline model in the next section will emphasize the firms' forward-looking decisions of entry, exit, and offshoring, fully incorporating the endogenous evolution of *market structure*. Furthermore, I will incorporate heterogeneous *organizational types* of firms (i.e., specialized versus conglomerate structures) as a robustness check (Appendix A.2.1). By contrast, the firm's *size*, *age*, and *technological/product generations* do not show clear patterns, and hence I will abstract from these aspects and refer the reader to Igami (2014) for further details on product innovation in the HDD industry.

3 Model

The goal of this section is to incorporate the endogenous evolution of market structure in a tractable and estimable model, to analyze offshoring and competition in a unified framework. The descriptive analysis in the previous section informs key modeling choices in what follows. In section 3.1, I will use a static Cournot example to gain insights into the incentives for cost-reducing investments, and to illustrate how an intuition from the static model might be reversed in a dynamic setting. I then build a fully dynamic model in sections 3.2 through 3.5 for the subsequent structural analysis.

3.1 A Static Cournot Example

The relationship between offshoring and competition can be complex in a dynamic setting. This subsection uses a static Cournot model to facilitate an intuitive understanding as to

how the incentives to offshore may change with market structure. This stylized illustration serves to motivate the development of a fully dynamic model of entry/exit and offshoring in the remainder of this section.

Let N and N^* represent the numbers of firms that produce homogeneous goods in the North (“home”) and the South (“offshore”), respectively. They compete in a single global product market. Home firms produce at a common and constant marginal cost mc , and offshore firms at $mc^* < mc$. Assume a linear (inverse) demand, $P = 1 - Q$, where Q is the aggregate output. Each firm chooses its output q_i (or q_i^*) to maximize its profit, $\pi_i = (P - mc)q_i$ or $\pi_i^* = (P - mc^*)q_i^*$. The Nash equilibrium outputs are

$$\begin{aligned} q_i &= (N + N^* + 1)^{-1} [(N^* + 1)(1 - mc) - N^*(1 - mc^*)], \text{ and} \\ q_i^* &= (N + N^* + 1)^{-1} [(N + 1)(1 - mc^*) - N(1 - mc)], \end{aligned}$$

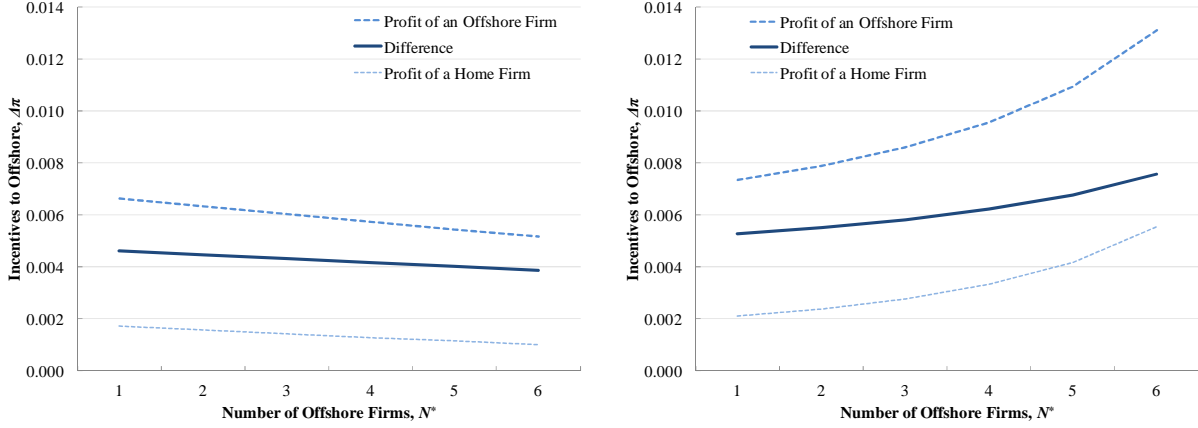
as long as the levels of mc and mc^* ensure positive outputs.

The most basic comparative static of this Cournot model is that a firm’s profit decreases with competition (i.e., a higher N or N^*) because of business-stealing and a downward pressure on the price. Moreover, even if the total number of firms, $N + N^*$, remains constant, more offshore producers (a higher N^* , with a commensurate reduction in N) mean lower π_i and π_i^* because outputs are strategic substitutes in Cournot competition. The reduction of π_i and π_i^* also entails a shrinking gap between them; that is, $\Delta\pi \equiv \pi_i^* - \pi_i$ decreases with a higher N^* , and hence the reduced incentives to offshore, as Figure 3 (left) illustrates. Thus, from a purely static perspective, offshoring by some firms would seem to discourage further offshoring by the other home firms.

Once we start considering the dynamics of market structure, however, our prediction becomes more nuanced. Because a home firm produces at a higher marginal cost, its profit is lower than that of an offshore firm (i.e., $\pi_i < \pi_i^*$), which implies a higher propensity to exit in a standard model of entry and exit (to be specified in the next subsection). Through this channel, offshoring by some firms may induce exits of other home firms, and consequently reduce N more than proportionally. Figure 3 (right) shows that $\Delta\pi$ may increase as N^* increases and $(N + N^*)$ decreases.

Furthermore, knowing that the increasing presence of offshore firms could trigger shake-outs of home rivals, forward-looking firms in an oligopolistic market may engage in offshoring with strategic motives, in the spirit of a preemption game or as an act of predation. These

Figure 3: Strategic Substitutability May Be Reversed in a Dynamic Setting
Constant Total Number of Firms, $N + N^* = 20$ If Every Offshoring Induces Exit of Two Home Firms



Note: These numerical examples are based on $(mc, mc^*) = (0.09, 0.05)$ and designed for illustration purposes only. The left panel holds fixed the total number of firms at 20, whereas the right panel reduces N by 3 for every increase in N^* to emulate the exit-inducing effect of offshoring.

dynamic strategic incentives may change nonmonotonically with market structure, and hence whether the simple prediction of strategic substitution *à la* Cournot prevails in a dynamic setting is not obvious. Thus, incorporating these forces seems important for the understanding of the empirical relationship between competition and offshoring.

For these reasons, the remainder of this section builds a dynamic oligopoly model of offshoring with entry/exit to allow for the endogenous evolution of market structure.

3.2 Timing

Time is discrete with a finite horizon $t = 0, 1, 2, \dots, T$. The motivation for this finite-horizon setup is twofold. First, both the demand and the cost conditions changed rapidly in a nonstationary manner, and hence I choose to let the value and policy functions depend on t , which would be infeasible with an infinite horizon. Second, I avoid multiple equilibria by exploiting the finite-horizon, sequential-move setting with iid private cost shocks, and solving the game by backward induction (see the remainder of this section for further details).

A finite number of incumbent firms are indexed by i . In any year t , each incumbent firm is in one of the two locational/technological states, $s_{it} \in \{\text{North}, \text{South}\}$, and the industry state is their aggregation, $s_t \equiv \{s_{it}\}_i = (N_t, N_t^*)$, where N_t and N_t^* are the numbers of firms that produce in the North (“home”) and the South (“offshore”), respectively, and

$s_{-it} \equiv \{s_{jt}\}_{j \neq i}$.¹⁴ The transition of s_{it} is as follows. The game starts in year 0 with $N_0 \geq 0$ incumbents in the North and no firms in the South ($N_0^* = 0$). At the beginning of each year, an infinite number of potential entrants consider the prospect of entry in the North.¹⁵ They enter sequentially until the expected value of entry falls short of the cost of entry, κ^{ent} . In each year, a Northern incumbent may either exit the industry forever, continue producing in the North, or relocate its manufacturing plants by paying a sunk cost, κ , to start producing in the South from the next year at some lower manufacturing costs (“offshoring”).¹⁶ A post-offshoring incumbent chooses to either exit or stay in the industry.¹⁷

The timing of the game is as follows. Each year t starts with the process of sequential free (but not necessarily inexpensive) entry, followed by period competition, from which each firm earns period profit $\pi_t(s_{it}, s_{-it})$ given the industry-wide demand and cost conditions (embodied by time subscript in $\pi_t(\cdot)$, to be specified in section 4). All of these industry-wide features are common knowledge.

- After the period competition, N_t home firms draw iid private cost shocks $\varepsilon_{it} = (\varepsilon_{it}^0, \varepsilon_{it}^1, \varepsilon_{it}^2)$ and simultaneously take actions $a_{it} \in \{\text{exit, home, offshore}\}$.
- Having observed these actions, N_t^* offshore firms (excluding those home firms that have just decided to offshore) draw iid private cost shocks $\varepsilon_{it}^* = (\varepsilon_{it}^{0*}, \varepsilon_{it}^{1*})$ and simultaneously take actions $a_{it}^* \in \{\text{exit, stay}\}$.
- Based on these actions of firms, market structure transits from s_t to s_{t+1} . The demand and cost conditions evolve exogenously.

Private cost shocks reflect each firm’s informational, managerial, and organizational conditions of transient nature. I focus on anonymous, type-symmetric pure strategy, which

¹⁴I follow the notational convention in international economics to denote “foreign” variables by $*$.

¹⁵One can imagine entrants in the South as well, but I choose not to model this possibility, because the data contain no such cases, except for a single fringe firm American managers in Singapore founded toward the end of the sample period. Industry sources suggest Silicon Valley was the obvious place for high-tech startups because of its concentration of human capital and venture-funding opportunities.

¹⁶In theory, firms might adjust home and offshore outputs in a *continuous* manner. In the data, however, most firms completely switch assembly locations within a year. Therefore, I model offshoring as a dynamic *discrete* choice.

¹⁷One can imagine offshore firms returning home (“reshoring”) as well, but I choose not to model this possibility because the data contain no such cases. No major reshoring cases have been recorded in the HDD industry to date. Likewise, I do not model further relocation after the first offshoring, because Singapore was by far the most prominent offshore assembly location during the sample period, after which Malaysia, Thailand, and China started catching up, but mostly as an extension of the Singapore-centered global supply chain.

maps these cost draws to a discrete choice, in the spirit of a static entry game with private information *à la* Seim (2006). To facilitate both the solution and the estimation of the model, I assume $\varepsilon_{it}(a_{it})$ is iid extreme value.

Besides the variable profit $\pi_t(s_{it}, s_{-it})$, active firms may earn (pay) some fixed profit (cost), ϕ , which reflects fringe benefits such as licensing revenues, net of continual investment in technologies and production facilities to keep up with the industry-wide trend of quality improvement: Kryder’s Law.¹⁸ I set scrap values to zero because of this fast rate of obsolescence.

3.3 Period Profit

Each year, the demand and production-cost conditions (D_t, C_t) , the firm’s own locational status (s_{it}) , and the other firms’ status (s_{-it}) completely determine the firm’s period profit,

$$\pi_{it} = \pi(s_{it}, s_{-it}; D_t, C_t). \quad (1)$$

The demand system D_t provides a mapping between the aggregate price and quantity of HDDs. The cost function reflects the relationship between each firm’s outputs and production costs, conditional on its plant location. Section 4 specifies D_t and C_t .

The HDDs are high-tech commodities with limited scope for differentiation besides product category, and hence I assume Cournot competition, and focus on anonymous, type-symmetric Nash equilibrium in the spot market.¹⁹ Thus the market structure (summarized by the industry state s_t , including s_{it}), along with D_t and C_t , completely determines each firm’s equilibrium profit from period competition. This formulation allows us to handle the dynamic oligopoly game of offshoring and entry/exit in a parsimonious state space, despite a considerably higher number of firms in the data (up to 30) than in typical applications of a dynamic game (between two and four).

¹⁸Kryder’s Law says the areal density (and hence information-storage capacity) of an HDD doubles every 13 months, which is faster than Moore’s Law in the semiconductor industry (i.e., the circuit density of chips doubles every 18 months). The analysis of Kryder’s Law is outside the scope of this paper. See Lerner (1997) for the related empirical analysis.

¹⁹Another motivation for the Cournot competition is that production facilities take time to build, up to a year. Hence we can invoke Kreps and Scheinkman’s (1983) argument that capacity building followed by pricing leads to Cournot outcomes. Note that if capacity adjustments were a truly long-run factor, we would have to model its dynamics explicitly. However, fast obsolescence due to the aforementioned Kryder’s Law ensures the medium-run nature of capacity adjustments in the context of the HDD industry. I thank Igal Hendel for pointing this out.

3.4 Dynamic Optimization

When their turns to move arrive, firms make their dynamic discrete choices of entry, exit, and offshoring to maximize their expected values. They discount their future stream of profits by a factor $\beta \in (0, 1)$, with rational expectations regarding both the endogenous evolution of market structure and the exogenous evolution of demand and production costs.²⁰

The following Bellman equations characterize the dynamic programming problems of active firms²¹:

$$V_t(s_t, \varepsilon_{it}) = \pi_t(s_t) + \max \left\{ \begin{array}{c} \varepsilon_{it}^0, \\ \phi + \beta E[V_{t+1}(s_{t+1}, \varepsilon_{it+1}) | s_t, \varepsilon_{it}] + \varepsilon_{it}^1, \\ \phi + \beta E[V_{t+1}^*(s_{t+1}, \varepsilon_{it+1}) | s_t, \varepsilon_{it}] - \kappa + \varepsilon_{it}^2 \end{array} \right\}, \text{ and} \quad (2)$$

$$V_t^*(s_t, \varepsilon_{it}) = \pi_t^*(s_t) + \max \left\{ \begin{array}{c} \varepsilon_{it}^0, \\ \phi + \beta E[V_{t+1}^*(s_{t+1}, \varepsilon_{it+1}) | s_t, \varepsilon_{it}] + \varepsilon_{it}^1 \end{array} \right\}, \quad (3)$$

subject to the perceived law of motion governing s_t . The expectations are over the other firms' choices, and hence over the realizations of their private cost shocks. For a potential entrant, the problem is simply

$$\max \{0, V_t(s_t) - \kappa^{ent}\}, \quad (4)$$

so that free entry implies

$$V_t(s_t) \leq \kappa^{ent}. \quad (5)$$

Besides the components of period profit functions, the key parameters of this dynamic discrete game are the sunk cost of offshoring, κ , that of entry for potential entrants, κ^{ent} , and the fixed benefit/cost of operation, ϕ .²²

²⁰I assume firms know the entire history of $\{(D_t, C_t)\}_t$ from the beginning, because *DISK/TREND Reports* suggests the existence of the industry-wide consensus on “technological roadmaps,” which appear to accurately predict the subsequent development.

²¹For notational simplicity, I suppress ε_{it}^0 , ε_{it}^1 , and ε_{it}^2 from the argument of $V_t(s_t)$.

²²I normalize the scrap value upon exit to zero and omit it from the model because *DISK/TREND Reports* rarely indicates any profitable sales of facilities or equipment when firms exit the market, which seems consistent with the industry's fast pace of obsolescence.

3.5 Equilibrium

I solve this finite-horizon, sequential-move dynamic discrete game with private information for a Perfect Bayesian Equilibrium (PBE) in type-symmetric pure strategies. Three features of the model are important to ensure computational feasibility and avoid multiple equilibria. First, because private information is merely in the form of iid cost shocks associated with each firm's discrete alternatives, $\varepsilon(a_{it})$, and *not* in the form of persistent heterogeneity, the firm's belief over off-path realizations of $\varepsilon(a_{-it})$ does not affect its payoff.²³ That is, the firm's payoff is affected by its rivals' cost shocks only through their actual choices, and *not* by the specific realizations of $\varepsilon(a_{-it})$, so firms hold perfect information on the payoff-relevant part of past history. Second, different types of firms move sequentially after observing the entry/exit/offshoring choices of earlier movers. At its turn to move, the firm (or the same type of firms with symmetric strategies) is effectively solving a single-agent problem based on its expectation over the subsequent evolution of market structure. Third, these two features and the finite-horizon formulation allow us to solve the model by backward induction.

I assume the terminal values associated with a firm's states, $s_{iT} \in \{\text{North}, \text{South}\}$, are²⁴

$$(V_T, V_T^*) = \left(\sum_{\tau=T}^{\infty} \beta^\tau \pi_T(s_T), \sum_{\tau=T}^{\infty} \beta^\tau \pi_T^*(s_T) \right). \quad (6)$$

In year $T - 1$, a home firm's problem (aside from maximizing its period profit) is

$$\max \left\{ \varepsilon_{i,T-1}^0, \phi + \beta E[V_T(s_T) | s_{T-1}] + \varepsilon_{i,T-1}^1, \phi + \beta E[V_T^*(s_T) | s_{T-1}] - \kappa + \varepsilon_{i,T-1}^2 \right\}.$$

I follow Rust (1987) to exploit the property of the iid logit errors, $\varepsilon_{it}(a_{it})$, to obtain a closed-form expression for the expected value before observing $\varepsilon_{it}(a_{it})$,

$$E_{\varepsilon_{i,T-1}} [V_{T-1}(s_{T-1}, \varepsilon_{i,T-1}) | s_{T-1}] = \pi_{T-1}(s_{T-1}) + \gamma \\ + \ln [\exp(0) + \exp(\phi + \beta E[V_T(s_T) | s_{T-1}]) + \exp(\phi + \beta E[V_T^*(s_T) | s_{T-1}] - \kappa)],$$

²³Because PBE and sequential equilibrium (SE) differ only in terms of restrictions on off-path beliefs, we may alternatively use SE as a solution concept for the same results.

²⁴I am reconciling the finite-horizon model with the reality in which the world did not actually end in 1998, by assuming the state stops evolving after year T . Alternatively, I may anchor the terminal values to some auxiliary data (if available) that would cover the periods after 1998, the final year of my data set. The market capitalization of the surviving firms as of 1998 might be a natural candidate, which, combined with net debt, would represent their enterprise values. However, I stopped pursuing this approach because of (1) the survivorship bias, (2) the presence of conglomerates, and (3) the omission of private firms.

where γ is the Euler constant. A similar expression holds for the offshore firms.²⁵ In this manner, I can write the expected value functions from year T all the way back to year 0. The associated choice probabilities (policy functions) will provide a basis for the MLE.

4 Estimation

My empirical approach takes three steps. First, I estimate the demand system. Second, I recover the marginal costs of production separately for the North and the South, from the demand estimates and the observed market shares of home and offshore firms in the data, exploiting the first-order conditions of the firms' period-profit maximization. These static demand and cost estimates for each year permit the calculation of period profit for each class of firms, in each year, under any market structure s_t . Third, I embed these period profits into the dynamic discrete game of offshoring and entry/exit, which I solve to estimate the sunk costs of offshoring, entry, and continued operation.

4.1 Demand

The dynamic oligopoly game framework in the previous section assumes homogeneity of HDDs, but the empirical demand analysis incorporates more details to exploit additional variations in the HDD sales data, in which the unit of observation is the combination of generation, quality, year t , buyer category, and geographical regions (see Igami 2014 for the details of the HDD sales data). I denote the generation-quality pair by “product category” j and suppress subscripts for the latter two dimensions. A buyer k purchasing an HDD of product category j , that is, a combination of generation g (diameter) and quality x (storage

²⁵The ex-ante value for an offshore firm is

$$E_{\varepsilon_{i,T-1}} [V_{T-1}^* (s_{T-1}, \varepsilon_{i,T-1}) | s_{T-1}] = \pi_{T-1}^* (s_{T-1}) + \gamma + \ln [\exp(0) + \exp(\phi + \beta E[V_T^* (s_T) | s_{T-1}])].$$

capacity in megabytes), enjoys utility²⁶

$$u_{kjt} = \alpha_0 + \alpha_1 p_{jt} + \alpha_2 \mathcal{I}(g_j = \text{new}) + \alpha_3 x_{jt} + \xi_{jt} + \epsilon_{kjt}, \quad (7)$$

with j subscript denoting product category (and *not* firm or brand),

where p_{jt} is the price, ξ_{jt} is the unobserved characteristics (most importantly, “design popularity” among buyers, as well as other unobserved attributes such as “reliability”), and ϵ_{kjt} is the idiosyncratic taste shock that is assumed iid extreme value (over buyers and generation-quality bins). The outside goods offer the normalized utility $u_{k0t} \equiv 0$, which represent *removable* HDDs (as opposed to *fixed* HDDs) and other storage devices.²⁷

Let $\bar{u}_{jt} \equiv \alpha_0 + \alpha_1 p_{jt} + \alpha_2 \mathcal{I}(g_j = \text{new}) + \alpha_3 x_{jt} + \xi_{jt}$ represent the mean utility from a category- j HDD whose market share is $ms_{jt} = \exp(\bar{u}_{jt}) / \sum_l \exp(\bar{u}_{lt})$. The shipment quantity is $Q_{jt} = ms_{jt} M_t$, where M_t is the size of the HDD market including the outside goods. Practically, M_t reflects all desktop PCs to be manufactured globally in a given year. Berry’s (1994) inversion provides the linear relationship,

$$\ln\left(\frac{ms_{jt}}{ms_{0t}}\right) = \alpha_1 p_{jt} + \alpha_2 \mathcal{I}(g_j = \text{new}) + \alpha_3 x_{jt} + \xi_{jt}, \quad (8)$$

where ms_{0t} is the market share of outside goods (removable HDDs). I estimate the taste parameters $(\alpha_1, \alpha_2, \alpha_3)$ by instrumental variable (IV) regressions of this linear equation.

Sources of Identification

The demand parameters are identified by the time-series and cross-sectional variations in the data.²⁸ Three dimensions of cross-sectional variation exist. First, an HDD’s product category (denoted by j) is a pair of generation and quality. Two generations and 14 discrete quality levels exist, according to the industry convention reflected in *DISK/TREND Reports*. Second, data are recorded by buyer category, PC makers, and distributors/end-users. Third, data are recorded by geographical category, U.S. and non-U.S.

²⁶I suppress the time subscript t for simplicity. The demand side is static in the sense that buyers make new purchasing decisions every year. Multi-year contracting is not common, and hundreds of buyers (e.g., computer makers) are present during the sample period. I do not model HDDs as durable goods because of fast obsolescence due to Kryder’s Law, and also because the dynamics of re-purchasing cycles in the PC market is driven primarily by operating systems (e.g., Windows 95 and 98) or CPU chips (e.g., Intel’s Pentium III), which I assume evolve exogenously to the HDD market. See Igami (2014) for details.

²⁷Tape recorders, optical disk drives, and flash memory.

²⁸See Berry and Haile (2009) for nonparametric identification of static discrete-choice demand models, using the types of instruments I use in the following.

In the IV estimation, I use the following variables as instruments for p_j : (1) the prices in the other region and user category and (2) the number of product “models” (not firms). Hausman (1996) and Nevo (2001) use the first IV. The identifying assumption is that production-cost shocks are correlated across markets, whereas taste shocks are not. This assumption reflects the industry context in which HDD makers from across the globe compete in both the United States and elsewhere, whereas end users of HDDs (and hence of PCs) are more isolated geographically. Bresnahan (1981) and Berry, Levinsohn, and Pakes (1995) use the second IV, which exploits the proximity of rival products (in product space), that is, the negative correlation between markup and the number of “models” in oligopolies. The identifying assumption is that taste shocks (i.e., ξ_{jt}) in any given period are not correlated with the number of “models” in a particular product category j , which are outside my model.²⁹

The literature has used these two IVs with cross-sectional data and static competition, but their usefulness is unknown in the context of global industry dynamics. For this reason, I also investigated the results based on alternative, time-series orthogonality conditions in the style of Sweeting (2013), and obtained the price-coefficient estimates of approximately -3.20 , a range statistically indistinguishable at the 5% level from my preferred estimate of -3.28 based on the other IVs (see section 5.1, column 4 of Table 3).³⁰

4.2 Period Competition and Marginal Costs

Although multiple categories (generation-quality pairs) of HDDs were available in the market, the majority of sales was concentrated in only a few quality levels (capacity in MB) within each generation (see Figure 11, top, in Appendix A.1.3), because most of the PCs on sale at any point in time came equipped with “typical” HDDs of the year, which were pro-

²⁹The following observation motivates this IV. Firms need to make “model”-introduction decisions in prior years, without observing taste shocks in particular regions/user types in the following years. Hence this identifying assumption would be plausible as long as particular regions’/user types’ taste shocks are not serially correlated.

³⁰This third approach employs an additional identifying assumption that the unobserved quality, ξ_{jt} , evolves according to an AR(1) process,

$$\xi_{jt} = \rho \xi_{jt-1} + \nu_{jt},$$

where ρ is the autoregressive parameter, and ν_{jt} is the “innovation” (in the time-series sense) that is assumed iid across product categories and over time. We can form exclusion restrictions for ν_{jt} by assuming firms at t do not know the unpredictable parts ν_{jt+1} when they make dynamic decisions.

I intend this additional IV result as a robustness check and do not use it for the subsequent analysis of dynamics, because the AR(1) assumption on the demand side may potentially introduce some conceptual inconsistency with my other assumptions on the supply-side dynamics, in which I let firms form perfect foresight about the evolution of demand (for the purpose of alleviating the computational costs).

duced by most HDD makers. For this reason, I assume all active firms in each technological generation sell “composite” HDDs with the shipment-weighted mean quality and generation, rather than a range of diverse categories.

Cournot competition with heterogeneous costs (by plant location) characterizes the spot-market competition.³¹ Marginal costs of production in the North and the South, mc_t and mc_t^* , are assumed to be common across firms and constant with respect to quantity. Firm i maximizes profits

$$\pi_{it} = (P_t - mc_{it}) q_{it} \quad (9)$$

with respect to shipping quantity q_{it} , where P_t is the global price of a representative HDD (i.e., composite good of all categories) and the marginal cost mc_{it} depends on the plant location of firm i . Firm i ’s first-order condition is

$$P_t + \frac{\partial P}{\partial Q} q_{it} = mc_{it}. \quad (10)$$

Sources of Identification

For each year, we can infer the marginal costs of production, mc_t and mc_t^* , from equation (10) for both home and offshore firms. Because the unit of observation in the HDD sales data is product-category level—and not firm or brand level—I maintain symmetry across firms (up to plant locations and private cost shocks) as identifying assumptions. The data set contains each firm’s total revenue-based market share in the global HDD market. I use this information to calculate the average market shares by location (\bar{q}_t, \bar{q}_t^*) , which, together with P_t from the data and the estimates of $\partial P / \partial Q$, allow us to back out (mc_t, mc_t^*) . These static demand and cost estimates completely determine period profits of home and offshore firms (π_t, π_t^*) in each year, under any market structure. These period profits, in turn, constitute the building blocks for the value and policy functions, and hence the optimal choice probabilities to construct the likelihood function in the following.

³¹Besides the data constraint (i.e., firm- or brand-level prices and quantities are not systematically recorded), three additional considerations motivate the Cournot assumption. First, unlike automobiles or ready-to-eat cereals, HDD is a high-tech “commodity.” Buyers chiefly consider its price and category (i.e., form factor and storage capacity), within which the room for further differentiation is limited. Second, changes in production capacity take time, and hence price competition given installed capacities *à la* Kreps and Scheinkman (1983) characterize the spot market. Third, accounting records indicate that despite fierce competition with undifferentiated goods, the HDD makers seemed to enjoy non-zero (albeit razor-thin) profit margins on average.

4.3 Cost of Offshoring

These static demand and cost estimates from the previous two steps imply specific period profit for each type of firms, in each year, under each market structure. In the third and final step of estimation, I embed these variable profits into the dynamic discrete game model and solve it for a Perfect Bayesian Equilibrium by backward induction (see section 3 for details). The goal of this step is to obtain estimates for the dynamic parameters, (ϕ, κ) , by maximum likelihood.

By contrast, I do not intend to estimate the discount factor, β , because its identification is known to be impractical (c.f., Rust 1987). Likewise, although an additional parameter, the rate of change in sunk costs, δ , is desirable for a better fit of offshoring timing patterns, δ is difficult to estimate, so instead I will assume δ equals some constant, and subsequently conduct sensitivity analysis.

The contribution of a home firm i in year t to the likelihood is

$$f(a_{it}|s_t; \phi, \kappa) = pr(a_{it} = exit)^{\mathcal{I}(a_{it}=exit)} pr(a_{it} = home)^{\mathcal{I}(a_{it}=home)} pr(a_{it} = offshore)^{\mathcal{I}(a_{it}=offshore)},$$

where $pr(\cdot)$ is the probability that a firm in the North takes a particular action a_{it} :

$$\begin{aligned} pr(a_{it} = exit) &= \exp(0) / B, \\ pr(a_{it} = home) &= \exp(\phi + \beta E_\varepsilon V_{t+1}(s_{t+1})) / B, \text{ and} \\ pr(a_{it} = offshore) &= \exp(\phi + \beta E_\varepsilon V_{t+1}^*(s_{t+1}) - \delta^t \kappa) / B, \end{aligned} \tag{11}$$

where $B \equiv \exp(0) + \exp(\phi + \beta E_\varepsilon V_{t+1}(s_{t+1})) + \exp(\phi + \beta E_\varepsilon V_{t+1}^*(s_{t+1}) - \delta^t \kappa)$. The contributions of offshore firms take a similar form.

In the data, year t has (N_t, N_t^*) active firms in each location, of which (X_t, X_t^*) exit and O_t offshore. Denote the joint likelihood for year t of observing data $(N_t, N_t^*, X_t, X_t^*, O_t)$ by $\Pr(N_t, N_t^*, X_t, X_t^*, O_t; \phi, \kappa)$. Then the overall joint likelihood for $t = 0, 1, 2, \dots, T-1$ is $\Pr(N, N^*, X, X^*, O; \phi, \kappa) = \prod_{t=0}^{T-1} \Pr(N_t, N_t^*, X_t, X_t^*, O_t; \phi, \kappa)$. Thus the ML estimators for the fixed cost of operation ϕ and the base sunk cost of offshoring κ are

$$\arg \max_{\phi, \kappa} \ln [\Pr(N, N^*, X, X^*, O; \phi, \kappa)].$$

I show only ϕ and κ explicitly as arguments of the likelihood function, because I calibrate β and δ , and infer the sequence of entry costs $\{\kappa_t^{ent}\}_t$ from the free-entry condition in equation (5) when solving the model given each combination of candidate (ϕ, κ) values.

Sources of Identification

I obtain the static demand and cost estimates (and hence the implied period profits) from the HDD sales data and completely outside the dynamic estimation framework. As such, these static estimates, together with the observed entry/exit/offshoring choices in the panel data of HDD manufacturers, constitute the key inputs for identifying the dynamic parameters. For example, a large fixed cost ϕ will decrease the predicted value of $pr(a_{it} = home)$, $pr(a_{it} = offshore)$, and B , and hence increase the predicted optimal choice probability of exit, $pr(a_{it} = exit)$. Correspondingly, if a high fraction of active firms actually chooses to exit in the panel data, such a data pattern (i.e., high X_t/N_t) will lead to a large estimate of $\hat{\phi}$. Likewise, a large sunk cost of offshoring, κ , will decrease $pr(a_{it} = offshore)$, so the observed fractions of offshoring in the data (i.e., O_t/N_t) will pin down the MLE for $\hat{\kappa}$.³²

5 Results

5.1 Demand

Table 3 displays demand estimates. I employ two market definitions, broad (columns 1 and 2) and narrow (3 and 4). The former definition aggregates observations across both regions (U.S. and non-U.S.) and user types (computer makers and distributors/end users), in a manner consistent with the industry’s context of a single, global market. However, the data set contains richer variations across regions and user types, which we can exploit for improved precision of estimates. Moreover, the Hausman-Nevo IVs become available under the narrower market definition (i.e., by region/user type). All four estimates incorporate year dummies and allow for the time-varying unobserved product quality by diameter (ξ_j in equations [7] and [8]).

The IV estimates in columns (2) and (4) are generally more intuitive and statistically significant than the OLS estimates in columns (1) and (3). The price coefficient is negative ($\hat{\alpha}_1 < 0$), whereas both smaller size (3.5-inch diameter) and quality (the log of storage

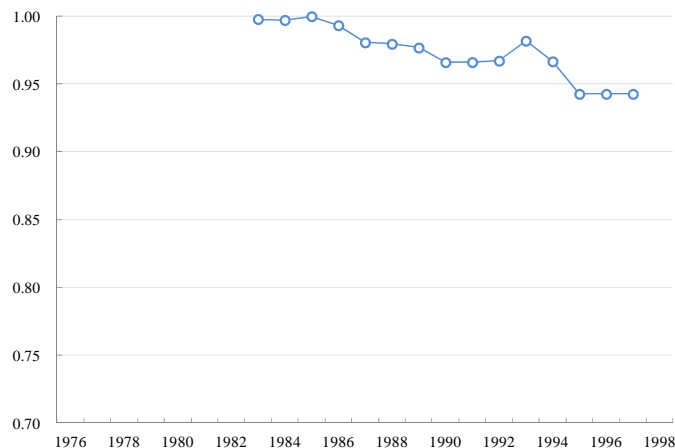
³²See Aguirregabiria and Suzuki (2014) for a formal identification discussion on dynamic entry models.

Table 3: Demand Estimates

Market definition:	Broad		Narrow	
Estimation method:	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)
Price (\$000)	-1.66*** (.36)	-2.99*** (.64)	-.93** (.38)	-3.28*** (.58)
Diameter = 3.5-inch	.84** (.39)	.75 (.50)	1.75*** (.27)	.91** (.36)
Log Capacity (MB)	.18 (.25)	.87*** (.31)	.04 (.22)	1.20*** (.27)
Year dummies	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>
Region/user dummies	—	—	<i>Yes</i>	<i>Yes</i>
Adjusted R^2	.43	.29	.50	.27
Number of obs.	176	176	405	405
Partial R^2 for Price	—	.32	—	.16
P-value	—	.00	—	.00

Note: Standard errors in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

capacity) confer higher benefits ($\hat{\alpha}_2 > 0, \hat{\alpha}_3 > 0$) to the buyers. I use column (4) as my baseline result for the subsequent analyses, because of the improved availability of IVs and the variation in data.

Figure 4: Cost Advantage of Offshore Production
(MC*/MC ratio)

Note: The graph plots the estimated mc_t^*/mc_t in each year.

5.2 Marginal Costs

These demand estimates, the observed market shares, and the firms' first-order conditions (equation [10]) imply the marginal costs of production in home and offshore locations. Figure 4 shows offshore firms enjoyed lower costs of production, and this cost advantage has

slightly widened over years, presumably because information technologies such as the Internet lowered the costs of communication between offshore plants and headquarters at home.

Given the massive wave of offshoring, the magnitude of cost advantage might appear small, but I believe the difference of several percentage points is reasonable for three reasons. First, HDDs are high-tech commodities with limited scope of brand differentiation between firms, and hence a small cost difference is sufficient to generate a wide gap in market shares. Second, the manufacturing wage rate in Singapore was less than 60% of the U.S. rate (see Appendix table A.1.1), but labor is not the only input, and the costs of other inputs such as components and equipment do not vary much by location. Therefore, when the labor share of costs is 30% and the Singaporean wage rate is 60% of the U.S. rate, for example, the ratio of overall marginal costs, mc^*/mc , will be 0.88. Third, the marginal cost estimates conceptually incorporate any costs that are associated with the production and the sale of HDDs in the global market, including transport costs and international border effects. Although Singapore is famous for its openness to trade, offshore production is likely to involve some extra logistics costs, so that the ratio of effective marginal costs may well surpass 0.88 in the above numerical example. These three institutional considerations lead me to regard the estimates of mc^*/mc in the range of 0.94–0.98 as rather intuitive.³³

5.3 Offshoring Cost

Table 4 shows the MLEs of the mean fixed cost of operation, ϕ , and the base sunk cost of offshoring, κ . I use the panel of major firms (as in Figure 1), set $\beta = .8$ and $\delta = .95$ for my baseline estimates, and conduct sensitivity analysis in Table 5. The estimates suggest ϕ is positive (i.e., fixed profit rather than fixed cost) but statistically indistinguishable from zero, whereas κ is sizable. The κ estimates in the order of billions of dollars might appear implausibly high at first glance, but the actual sunk cost declines from this *base* level at an annual rate of 5%. The actual cost, $\delta^t \kappa$, falls below \$2 billion in year 1990, which is around the period in which most firms decided to offshore. These figures are comparable to the annual R&D budget and capital expenditure at specialized HDD manufacturers such as

³³As an external benchmark, *The Economist* (“Special Report: Outsourcing and Offshoring,” January 19, 2013) estimates the offshore manufacturing costs in China, Mexico, and India in the range of 90%–97% of the U.S. cost circa 2008, based on the data from management consultants (AlixPartners; McKinsey; Hackett). Although the specific destination countries and time period are different from the subject of this paper, these numbers suggest my marginal cost estimates are consistent with the beliefs of these practitioners.

Western Digital and Seagate Technology (between \$1 billion and \$3 billion).³⁴

Table 4: Estimates of the Dynamic Parameters

(\$ Billion)	Maximum Likelihood Estimates
Fixed cost of operation (ϕ)	0.07 [-0.09, 0.25]
Sunk cost of offshoring (κ)	4.31 [3.20, 5.85]
Log likelihood	-156.17

Note: The 95% confidence intervals, based on likelihood-ratio tests, are in brackets. See Table 5 and Appendix A.2 for robustness checks.

Table 5 shows the sensitivity of the dynamic parameter estimates with respect to the rate of change of offshoring costs, δ . The fixed-cost estimates, $\hat{\phi}$, do not appear to change systematically with δ , because ϕ mostly affects entry and exit but not offshoring. By contrast, the sunk-cost estimates, $\hat{\kappa}$, decrease with δ , because a higher growth rate of the offshoring costs leads to higher average costs of offshoring over time, and hence the model requires correspondingly lower levels of the base sunk costs to rationalize the offshoring rates in the data.

Table 5: Sensitivity Analysis

	$\delta = .90$	$\delta = .95$	$\delta = 1.00$	$\delta = 1.05$	$\delta = 1.10$	$\delta = 1.15$
Fixed cost of operation (ϕ)	0.05	0.07	0.08	0.08	0.06	0.05
Base sunk cost of offshoring (κ)	6.49	4.31	2.73	1.57	0.82	0.39
Log likelihood	-158.65	-156.17	-158.73	-167.08	-178.82	-190.23

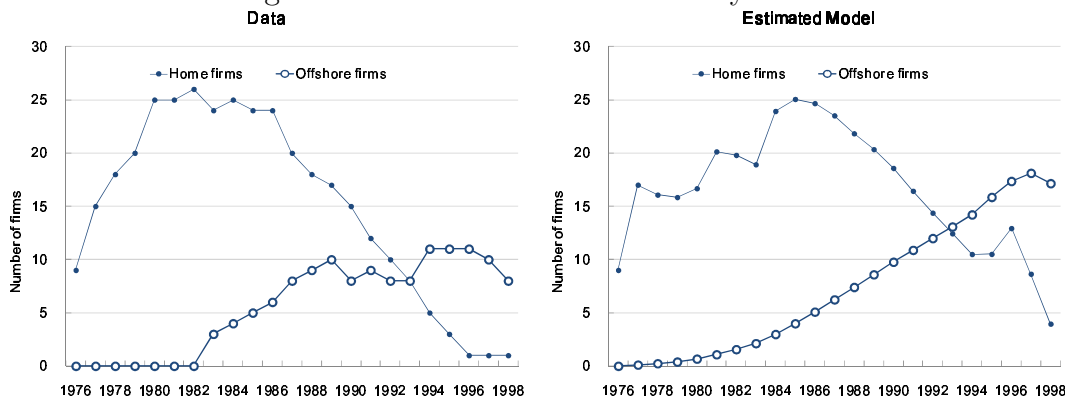
Note: As a reminder, the baseline parameter value for δ is .95.

The baseline estimates under $\delta = .95$ led to the log likelihood of -156.17 , which is higher than those from the other configurations. Thus I believe the baseline calibration represents a reasonable modeling choice to fit the industry dynamics of offshoring in the data.³⁵

³⁴Two caveats are in order regarding this ballpark comparison of economic and accounting costs. First, not all of these accounting items relate specifically to the offshore investments in Singapore and the neighboring countries. Second, my estimates incorporate *any* economic costs associated with the decision making and execution of offshoring, including cognitive, informational, and organizational costs as well as direct, tangible costs of relocating plants, equipment, and personnel. I expect the time and effort spent on trials and errors to make a global supply chain work, before the age of the Internet, to be a major component of offshoring sunk costs.

³⁵More specifically, offshoring costs consist of the physical costs of closing domestic plants, opening offshore plants, and moving equipment and key personnel, as well as intangible costs rooted in the logistics and

Figure 5: Fit of Market-Structure Dynamics



Note: Right panel displays the mean number of firms across 10,000 simulations of the estimated model.

5.4 Fit

Figure 5 suggests the estimated model fits the data reasonably well, replicating two central features of market-structure dynamics. First, the number of firms in the North peaks at 26 during the first half of the sample period, and then declines precipitously during the second half, as some of them move offshore while others exit (i.e., shakeout among home firms). Second, the number of firms in the South primarily increases from the middle of the sample period (i.e., growing dominance of offshore production toward the end). The estimated model does not replicate all of the wiggles in the data, and the fit is somewhat erratic for the last few years, presumably due to the finite-horizon formulation. Nevertheless, it appears to provide a simple benchmark against which we can compare alternative industry dynamics under different policy interventions, which are the focus of section 6.

5.5 How Market Structure Affects Offshoring

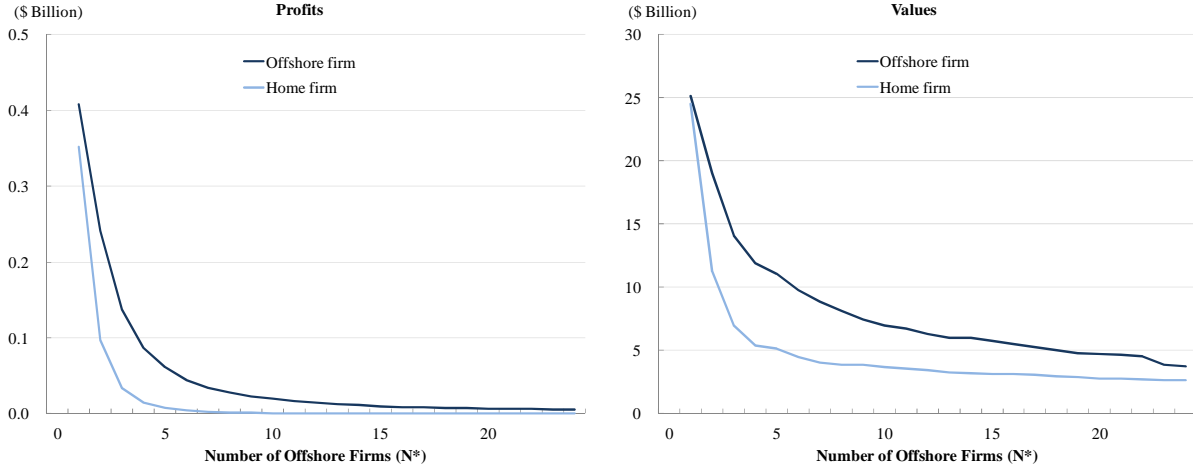
This section answers the first question of the paper, namely, how competition affects offshoring incentives.

Figure 6 (left) illustrates how period profits decline with increased competition from offshore rivals. As the number of firms increases, the aggregate output increases as well, putting a downward pressure on the global HDD price and dampening profit margins. An individual firm's market share will decline because of the business-stealing effect. The impact of additional rivals operates through these two channels to decrease a firm's equilibrium

management. One would expect these underlying cost components to change only gradually across time, and hence the current specification of the constant-rate change would be both parsimonious and practical.

profit in Cournot competition. The key feature of the estimated model with heterogeneous costs is that the increased pressure from offshore firms hits home firms' profits harder than those of other offshore firms. Because home firms produce in a relatively high-cost location, five offshore rivals will be sufficient to drive a home firm's profit down to negligible levels, whereas offshore firms facing the same competition can still secure profits in the order of tens of millions of dollars. Thus the presence of additional offshore firms hurts home firms disproportionately more than offshore firms.

Figure 6: Effects of Market Structure on Profits and Values

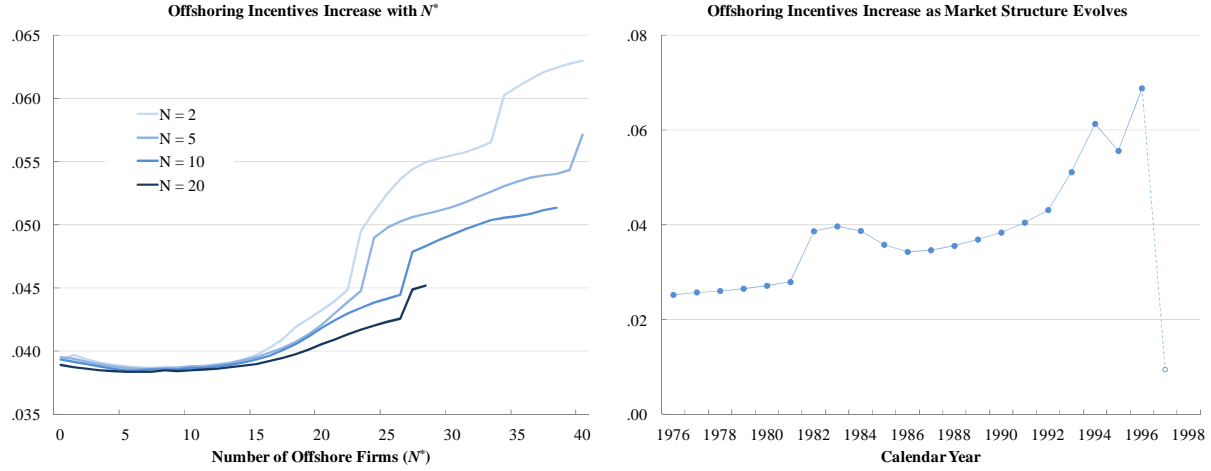


Note: The graphs show the profit and value functions in 1990 for market structures with $N = 1$ and $N^* \in \{1, 2, \dots\}$. The functions in other years share similar shapes.

Figure 6 (right) shows the dynamic counterpart to profit functions. As the number of offshore rivals increases, the value of a home firm, V , declines much faster than that of an offshore firm, V^* . The difference $(V^* - V)$ increases with N^* at first, and then decreases because everyone's profit will be eventually competed away with a large N^* . The model allows home firms to make dynamic discrete choices by comparing the expected values of offshore and home operations, so a larger $(V^* - V)$ implies more incentives to offshore.

Figure 7 (left) is the fully dynamic, empirical counterpart to Figure 3 in section 3.1, which illustrated strategic substitutability in the static Cournot example (and the possibility of its reversal in dynamics). Figure 7 (left) shows the incentives to offshore *increase* as more firms offshore, holding fixed the number of home firms. This pattern in the estimated policy function suggests offshoring breeds offshoring through competitive pressure. Figure 7 (right) illustrates its time pattern. Initially, all firms start operations in the North, and the incentives to offshore are not necessarily high. But once someone starts offshore production at a lower

Figure 7: Offshoring Breeds Offshoring



Note: The graphs show the equilibrium choice probability of offshoring. Left panel shows its values across different market structures in 1990 (the policy functions in other years exhibit similar shapes). Right panel shows its evolution along the actual time path of market structure shown in Figure 1 (top). The drop in 1997 is due to the finite-horizon computational setup and should not be interpreted economically.

cost, which puts downward pressure on the price and steals the rivals' market shares, the remaining home firms are increasingly forced to choose between offshoring for survival and staying home with increased chances of exit. Eventually, all home firms either offshore or exit, and offshore firms will dominate the industry.

6 Strategic Offshoring Policy

In this section, I conduct counterfactual simulations to assess the welfare performances of government interventions to encourage or discourage offshoring. First, I investigate the effect of offshoring on market structure in the long run, by simulating alternative industry dynamics when the cost of offshoring is prohibitively high (e.g., because of disruptions to global trade). Second, I simulate a unilateral intervention by the U.S. government. Third, I solve for strategic offshoring policies in Nash equilibrium, in which the U.S. and the non-U.S. governments intervene non-cooperatively.

6.1 Benchmark: No Offshoring

Section 5.5 analyzed the effect of market structure on home firms' offshoring incentives. This section asks the reverse question: How does the possibility of offshoring affect the evolution of market structure in the long run? The actual history of the HDD industry witnessed a

massive wave of offshoring to Singapore, whereas I run a counterfactual simulation of the world without offshoring, by setting the offshoring cost at a prohibitively high level, $\tilde{\kappa} = 4\hat{\kappa}$, and solving the dynamic game for a new industry equilibrium (PBE).

Figure 8 (left) shows that the total number of HDD firms would be higher in the no-offshoring counterfactual than in the baseline model. Moreover, the onset of shakeout (i.e., a rapid decrease of the number of firms) is delayed. A higher number of firms might appear to imply more fierce competition, but from an industry dynamics viewpoint, we should note that more firms chose to enter and lived longer precisely because no offshore rivals presented competitive threats. As section 5.5 showed, once some firms start offshore production, the other firms are increasingly pressured to choose between flying or dying, because of business-stealing and downward pressure on the global HDD price.

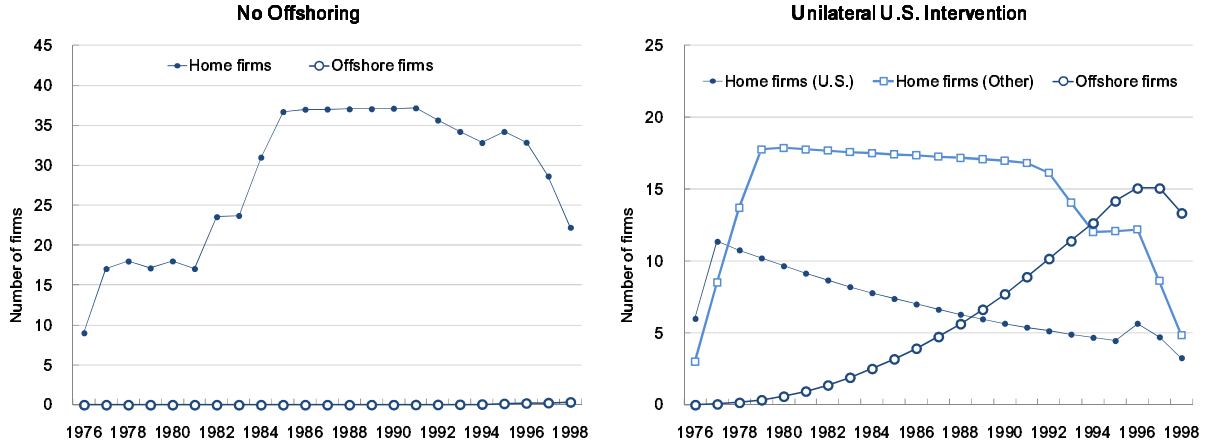
Therefore, offshoring plays the role of “drastic” innovation in Arrow’s (1962) sense; that is, a new mode of production lowers the innovators’ marginal costs so much that they will wipe out the rest of the industry and alter its market structure. Gort and Klepper (1982) and Klepper and Graddy (1990) documented historical episodes in which technical changes triggered shakeouts, and Sutton’s (1992, 1998, 2013) theory explained such empirical patterns by rising sunk costs. My comparison of industry dynamics with and without offshoring complements their historical-theoretical perspectives by providing new quantitative evidence from the context of globalization.

We can interpret this no-offshoring counterfactual as disruptions to global trade, the absence of free trade with Singapore, or a hypothetical situation in which Southern countries had not opened up for the HDD makers’ FDI: a world without Singapore. The welfare implication is clear but nuanced. On the one hand, the present value of consumer surplus declines from \$6.88 billion to \$6.82 billion because homemade HDDs are more costly and expensive. On the other hand, the present value of producer surplus (net of offshoring costs) increases from \$4.21 billion to \$7.70 billion because firms no longer have to pay the huge sunk cost of offshoring. This saving of sunk costs dominates the other effects, so the net impact on world welfare turns out to be positive, even though such situations harm consumers.

6.2 Unilateral Intervention

The previous section analyzed the case in which no firms could offshore, regardless of their nationalities. By contrast, this section analyzes the consequences of a unilateral intervention.

Figure 8: Counterfactuals with Higher Offshoring Costs



Note: The mean number of firms across 10,000 counterfactual simulations.

U.S. opinion polls indicate that 76%–95% of the respondents agree that “outsourcing of production and manufacturing work to foreign countries is a reason the U.S. economy is struggling and more people aren’t being hired.”³⁶ Unsurprisingly, politicians often blame domestic unemployment on “companies shipping jobs overseas.”³⁷ Given the public’s hostility toward offshoring, a thought experiment seems warranted to simulate and understand the likely consequences of anti-offshoring policies.

In practice, governments have tried a variety of measures to help or hinder offshoring. On the one hand, government agencies such as Japan External Trade Organization (JETRO) help domestic firms’ FDI by facilitating the opening of offices and establishments abroad and providing information and networking opportunities. On the other hand, layoffs and plant closures are heavily regulated in countries such as France or Germany, and recent disputes over Boeing’s plan to assemble new jets outside its home state of Washington illustrate that relocations could become a highly politicized issue. Modeling these specific channels of political economy is beyond the scope of this paper, but we can interpret κ as a “reduced-form” representation of these policy instruments that could potentially affect the effective cost of offshoring from the firms’ perspectives.

I operationalize this counterfactual experiment by adding nationality to the Northern locations, so that firms now belong to one of the three locational states instead of two: {US, Other North, South}. Let $(N_t^{US}, N_t^{Other}, N_t^*)$ denote the number of firms at time t in

³⁶ *The Wall Street Journal*, “Americans Sour on Free Trade,” October 2010. *Gallup Poll*, “Americans’ Top Job-Creation Idea: Stop Sending Work Overseas,” March 31, 2011.

³⁷ *The Wall Street Journal*, “Tax Break for ‘Shipping Jobs Overseas’ — Explained,” October 5, 2012.

the United States, the other Northern countries, and offshore locations, respectively. The game starts with $(N_0^{US}, N_0^{Other}, N_0^*) = (6, 3, 0)$ to match the data. The possible actions for the U.S. and the other Northern firms are just like those of the home firms in the baseline model (i.e., each of them decides whether to exit, stay home, or offshore), except that the cost of offshoring for American firms is prohibitively high, whereas the other Northern firms face the same cost as in the baseline estimate: $(\kappa^{US}, \kappa^{Other}) = (4\hat{\kappa}, \hat{\kappa})$. Regarding the order of moves, I assume American firms move first, followed by the other Northern firms, and then by offshore firms, because Silicon Valley was widely regarded as the center of the industry and American firms account for the majority of HDD makers in the data and are therefore more visible to the industry participants than the other nationals. I assume free (but not necessarily inexpensive) entry in both the United States and the other Northern countries.

Figure 8 (right) shows the unilateral intervention by the U.S. government results in American firms' rapid decline, because the other nationals continue offshoring to reduce manufacturing costs, and eventually drive high-cost firms out of the global HDD market. Potential entrants in the United States expect less profitable futures than their counterparts elsewhere, and hence fewer American entrepreneurs enter the market. Therefore, unilaterally stopping domestic firms from offshoring does not seem appealing. In the short run, the intervention may preserve the assembly-line jobs at a few surviving American firms at home, but in the long run, such a policy risks the survival of the entire HDD industry on domestic soil. Thus the policy implication of this exercise appears to be: If you can't beat them, join them.

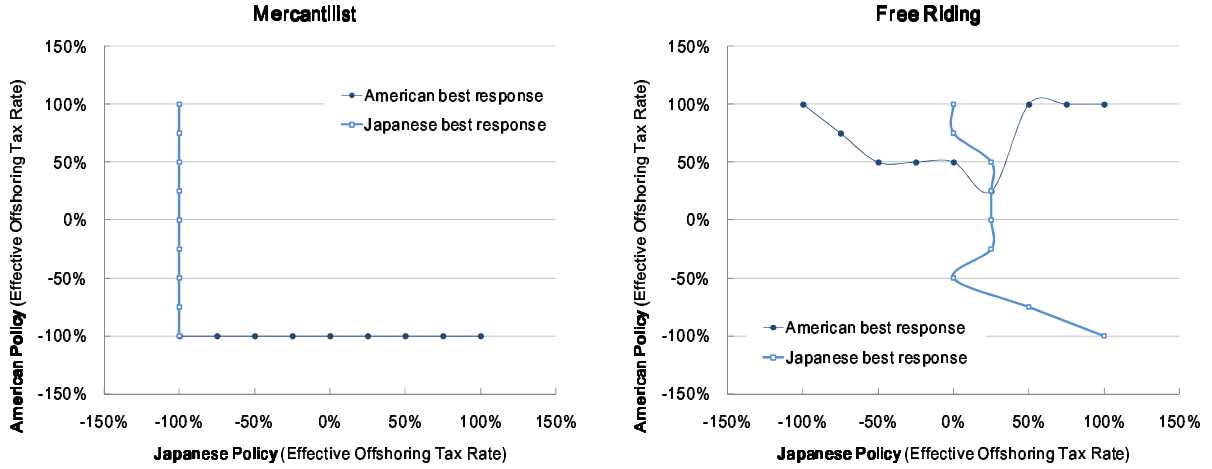
6.3 Government Policies in Nash Equilibrium

Universal or unilateral, the hypothetical policies in the preceding sections may not constitute a world-wide equilibrium, because governments can respond to each other's policies in reality, usually in a non-cooperative manner. Therefore, this section analyzes government interventions in Nash equilibrium, under two alternative assumptions regarding the objectives of the Northern governments: (1) national producer surplus and (2) national welfare.

Operationally, I continue using the augmented framework of the previous section (i.e., two Northern countries with heterogeneous costs of offshoring), but now allow the "other" government (e.g., Japan) to change its own offshoring policy in response to the U.S. policy. Each set of $(\kappa^{US}, \kappa^{Other})$, which are now the governments' strategic policy instruments,

entails a resulting global industry equilibrium and the welfare outcomes for the national economies. The computation of a PBE takes a long time, so I solve the model for PBE and evaluate the two countries' welfare outcomes under 81 combinations of the κ s (i.e., in a discretized grid with nine different levels of κ for each government) and impute the governments' reaction curves by interpolation. To allow the possibilities of both “taxing” and “subsidizing,” I set the range of the effective “tax” rate to $[-100\%, +100\%]$.

Figure 9: Nash Offshoring Policies



Note: The best-response “tax” rates are based on the average of 10,000 simulated PBE outcomes of the dynamic offshoring game, for each of the 81 combinations of $(\kappa^{US}, \kappa^{Other})$. The other Northern country is labeled as Japan because it has been home to most of the non-U.S. HDD makers to date.

Figure 9 (left) shows the two governments' reaction curves when both of them seek to maximize their respective national producer surplus, which suggests maximal subsidy is the dominant strategy for both. As the unilateral-intervention experiment has epitomized, hindering offshoring would risk the survival of national industries (and hence national producer surplus), so the “mercantilist” governments would rather encourage offshoring of domestic firms in the hope of driving foreign firms out of the global HDD market. Thus, when the governments prioritize the strengthening of their national industries, the resulting Nash equilibrium features an international race to go to Singapore, which might run counter to the conventional protectionist instincts.

Figure 9 (right) shows the reaction curves when the governments maximize their national welfare. The best responses become nonmonotonic because each government faces a subtle tradeoff between the benefits and costs of offshoring (i.e., more firms' offshoring will increase not only consumer surplus and producer surplus, but also the sunk cost paid by firms and/or the government). Contrary to the “mercantilist” case, they end up imposing moderate

“taxes” on offshoring because each country’s consumers hope to free-ride on the offshoring (i.e., cost reduction) efforts of the other country’s firms, rather than spend their public funds to help domestic firms pay offshoring costs. The following observations would help us understand the nature of this “free-riding” equilibrium. Consumer surplus is a larger component of welfare than producer surplus in the global HDD market, and the sunk costs of offshoring are also sizable. Because the product market is global, consumers in any country can benefit from the cost-reduction efforts of any firms regardless of nationality. Thus national welfare-maximizing governments would care more about minimizing the national sunk costs (including “subsidies”) than promoting national industries. These reasons are why the governments would rather discourage domestic firms from offshoring and seek to benefit from foreign firms’ efforts.

6.4 Discussion

These counterfactual experiments highlight the benefits and costs of offshoring and government interventions, from three angles. First, the case of no offshoring showed that offshoring is pro-competitive and beneficial to the world’s consumers, although the overall welfare implication is nuanced because of the high sunk costs of relocation (incurred by firms). Second, the unilateral intervention scenario suggested the unintended consequence of trying to protect domestic industry (in the short run) could be the decline of domestic firms (in the long run). Third, the fully strategic government policies resulted in an international “subsidy” race when the governments sought to maximize national producer surplus, whereas the welfare-maximizing policies in Nash equilibrium would actually entail “taxation” on domestic firms’ offshoring, to free-ride on foreign firms’ cost-reduction efforts. Undoubtedly, a more complicated political economy would shape the governments’ objectives in reality, but regardless of their specific goals, policy makers should understand that the dynamic forces of global competition will determine the consequences of any interventions. These are the insights we learn from the dynamic strategic framework.

7 Conclusion

This paper studied the strategic industry dynamics of offshoring, and proposed a conceptual and empirical framework to understand the product-market aspect of offshoring in oligopolis-

tic markets, with application to the global HDD industry. The estimates suggest offshore firms achieve lower costs of production and subsequently exert competitive pressure on the remaining home firms to choose between flying and dying. Thus, offshoring breeds offshoring and plays the role of “drastic” innovation (Arrow 1962) in a strategic and dynamic sense. Given such dynamics of global competition, discouraging domestic firms from offshoring would risk their survival in the long run, so an insight from this analysis appears to be: If you can’t beat them, join them.

Offshoring poses different tradeoffs for different players. For firms, offshoring represents an expensive investment in cost reduction that becomes increasingly necessary for survival. For consumers, offshoring by any firm is beneficial because it makes HDDs cheaper and the market more competitive.³⁸ Consequently, from the perspective of the Northern governments, different objectives call for radically different policy interventions (i.e., effective “subsidies” or “taxes”), which I believe partially explains why offshoring is such a controversial topic, besides emotional reactions to the prospect of job losses.

Some of these results would be specific to the HDD market, but the implications should be testable in other industries. The economic forces my analysis highlighted are general and expected to be influential in other high-tech markets, because these product markets tend to be global oligopolies as well.

³⁸That is, unless the consumer happens to work in the HDD assembly line and subsequently loses his or her job due to offshoring. The analysis of labor-market impacts is beyond the scope of this paper.

Appendix

A.1 Additional Descriptive Evidence

A.1.1 Labor Cost in South-East Asia

Table 6 compares the Singaporean wage rate in manufacturing with those in other South-East Asian countries and the United States. Three patterns emerge. First, the Singaporean wage rate was lower than that in the United States throughout the 1980s and 1990s. Second, the rise of the wage rate in Singapore was the fastest of all countries in the table, including the United States. Third, the other South-East Asian countries had much lower wage rates.

Table 6: Labor-Cost Advantage of Offshoring

	1983	1985	1988	1990	1993	1995
Hourly Wage Rate for Manufacturing (US\$)						
United States	8.83	9.54	10.19	10.83	11.74	12.37
Singapore	1.49	2.47	2.67	3.78	5.38	7.33
Malaysia	–	1.41	1.34	1.39	1.74	2.01*
Thailand	0.43	0.54	0.62	1.03	1.25	1.41
Philippines	0.59	0.55	0.74	1.02	1.07	–
Indonesia	0.13	0.3**	0.38	0.60	0.92***	–
(as a percent of United States)						
United States	100	100	100	100	100	100
Singapore	17	26	26	35	46	59
Malaysia	–	15	13	13	15	16
Thailand	5	6	6	10	11	11
Philippines	7	6	7	9	9	–
Indonesia	1	3	4	6	8	–

Note: *, **, and *** indicate data in 1994, 1986, and 1992, respectively.

Source: ILO, U.S. Department of Labor, and UNIDO, *cit in* McKendrick, Doner, and Haggard (1996: table 6.1).

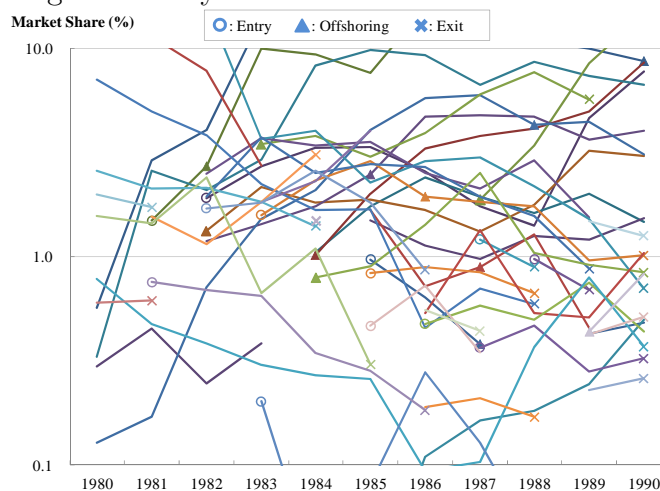
In terms of modeling choices, these patterns have led me to allow for changes in the marginal costs of production over time, in both home and offshore locations. I abstract from the other South-East Asian countries because McKendrick et al. (2000) suggest they were a part of supply chains centered in Singapore, and hence did not constitute independent, alternative locations for offshoring firms in the HDD industry.

A.1.2 Within-location Firm Heterogeneity

The baseline model assumes homogeneity of firms within each location (home and offshore) *up to private cost shocks* that are iid across firms and over time. One obvious question asks

to what extent such formulations capture the actual data patterns of firm heterogeneity. Figure 10 plots the transition of market share, with each line representing a unique firm. The overall pattern indicates a high variability of market shares across firms, as well as high volatility over time, both of which appear broadly consistent with the way firm heterogeneity is modeled via idiosyncratic shocks to dynamic discrete choices. Of course, some firms stayed above 1% and others below 1%, for example, so some persistence seems to exist in individual firms' market shares. Nevertheless, firms change their ranks so frequently and significantly that constructing a meaningful measure of persistent productivity is difficult.

Figure 10: High Volatility of Firm Size Blurs Persistent Heterogeneity



Another related question is whether more (or less) productive firms self-select into offshoring (or exit). Let us look at Figure 10 again, which marks with triangles the years in which firms decide to offshore. These triangles are scattered, showing no particular tendencies. That is, some firms fly early, whereas others delay; some firms enjoy relatively high market shares before going offshore, whereas others serve less than 1% of the market when they offshore. By contrast, a growth *after* offshoring appears more salient than *before* it, as shown in Figure 2 (right). Likewise, exits (marked by crosses) occur all over the place, showing no clear patterns. Some firms exit despite their respectable market shares, whereas others shrink below 1% and subsequently disappear. The latter trajectory becomes more frequent toward the end of the 1980s, with the growing competitive pressure from offshore rivals, which is one of the main data features my dynamic oligopoly game model explains.

Table 7 further confirms these impressions, by showing the lack of clear relationships between firms' market share and their propensity to either offshore or exit.

Table 7: Do Better Firms Self-select into Offshoring?

Quartile based on 1976–85 market share	Number of Firms	% offshored by 1991	% exited by 1991 (without offshoring)
1st quartile	11	36.4	36.4
2nd quartile	11	27.3	63.6
3rd quartile	11	36.4	36.4
4th quartile	11	18.2	63.6

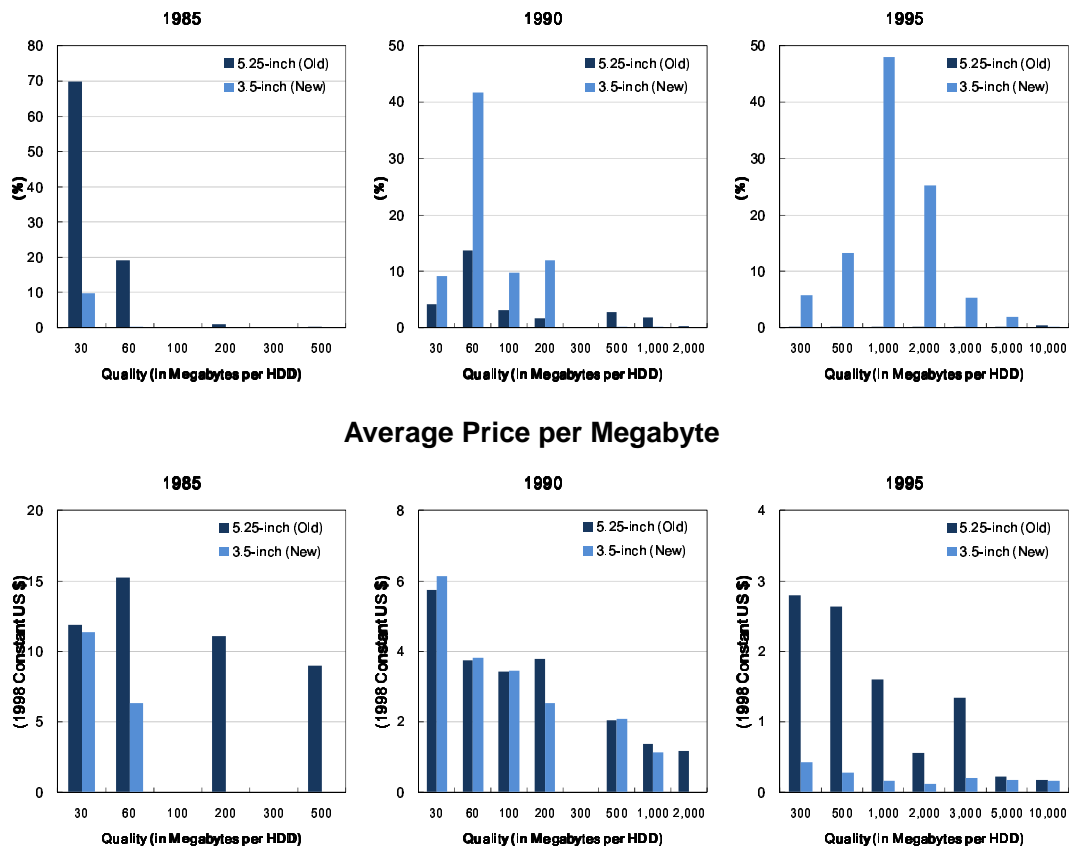
Thus these observed relationships (or lack thereof) between market shares and the propensity to offshore or exit seem to agree with the modeling of firm heterogeneity via iid shocks. See section A.2.1 for a robustness check with heterogeneous organizational types, which is the only firm characteristic that predicted offshoring propensities in a statistically significant manner in my exploratory data analysis (Table 2).

A.1.3 Product Diversity

The majority of sales was concentrated in only a few quality levels (capacity in MB) within each generation (Figure 11, top), because most of the PCs on sale at any point in time came equipped with “typical” HDDs of the year, which were produced by most HDD makers. For this reason, I assume all active firms in each technological generation sell “composite” HDDs with the mean quality, rather than a range of diverse categories.

This specification would be a bad approximation of the reality if, for example, top-quality HDDs earned fat premiums relative to typical ones. However, Figure 11 (bottom) shows the price per quality unit (MB) either remains flat or declines with quality (MB per HDD), suggesting higher-quality HDDs offered more economical bundles of information storage capacity to the buyers, and not exactly a premium category that is particularly profitable for the sellers. This observation alone would not necessarily rule out the possibility that some firms earned above-average profits in certain special categories, but I choose to maintain the characterization of HDDs as highly substitutable high-tech commodities in modeling the dynamic oligopoly game.

Figure 11: Shipment and Price/MB by Product Category
Industry-wide Market Share



Note: Average prices are calculated by dividing total revenues by shipment quantities. Minor product categories saw few shipments, and hence their average prices are not reliable.

A.2: Sensitivity and Robustness Checks

A.2.1: Heterogeneous Organizational Types

In this section, I augment the baseline model with heterogeneous firms and show the estimates for the offshoring costs of “high-” and “low-” type firms separately. The motivation for this exercise is twofold. First, theories of trade and offshoring have focused on heterogeneous firms and their self-selection into overseas activities. Second, the firms’ market shares (the proxy for size and productivity) exhibited little persistence over time (Appendix A.1.1) and statistically insignificant relationships with offshoring propensities, but the organizational type of firms (whether the firm is a specialized maker of HDDs) appeared to predict offshoring well (Table 2). Thus the analysis of an extended model with heterogeneous organizational types would be instructive from both theoretical and empirical perspectives.

Table 8: Estimates of the Dynamic Parameters

(\$ Billion)	Maximum Likelihood Estimates
Fixed cost of operation (ϕ)	0.09
Type-I firms’ sunk cost of offshoring (κ^I)	[-0.07, 0.26]
Type-II firms’ sunk cost of offshoring (κ^{II})	[0.62, 4.88]
	5.45
	[3.79, 7.60]
Log likelihood	-153.83

Note: The 95% confidence intervals, based on likelihood-ratio tests, are in brackets.

Specifically, the model will incorporate two types of firms in the home location, specialized (type I) and conglomerate (type II) firms, whose sunk costs of offshoring can be different (κ^I, κ^{II}). The preliminary regression suggests $\kappa^I < \kappa^{II}$, but I do not impose any restrictions on these parameters. I assume their marginal costs of production are identical (i.e., $mc_t^I = mc_t^{II} = mc_t \forall t$), because Appendix A.1 showed firm size is extremely volatile and I did not find any systematic difference between the two types in this respect. Likewise, I assume their marginal costs after offshoring are identical (i.e., $mc_t^{I*} = mc_t^{II*} = mc_t^* \forall t$). Let (N_t^I, N_t^{II}, N_t^*) denote the numbers of type-I firms at home, type-II firms at home, and offshore firms of either type, which will constitute the payoff-relevant industry state along with the demand and cost conditions in each year. Regarding the order of moves, I assume type-I firms at home move first, followed by type-II firms at home, and then by offshore firms. We can estimate this extended model in the same way as the baseline model, except that the last

step now contains three parameters $(\phi, \kappa^I, \kappa^{II})$ instead of two, and that the computation time grows exponentially with this kind of state-space extension. For this reason, I intend this augmented model and estimation result solely for the purpose of a robustness check.

Table 8 shows the MLEs. Type-I firms' sunk cost of offshoring is lower than that of type-II firms, a pattern that is consistent with the preliminary regression. Both $\hat{\kappa}^I$ and $\hat{\kappa}^{II}$ are outside the 95% confidence interval of each other, and hence organizational types matter statistically. The fit with the aggregate data pattern does not appear to change materially, and the shapes of the profit and value functions are similar to those in the baseline model. Thus I view the incorporation of additional firm heterogeneity primarily as a matter of additional details rather than something that could potentially alter the qualitative implications of the framework at the aggregate level.

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