Industry Dynamics of Offshoring:
The Case of Hard Disk Drives
Online Appendix

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This Online Appendix contains seven sections to supplement various aspects of the main analysis. Table 1 provides the table of contents and the corresponding sections in the main text.

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A. Additional Evidence on the Role of Offshoring in the HDD Industry

Section II's minimalist data-presentation style might have left some readers wondering whether: (i) offshoring was really the fundamental driving force of industry shakeout; (ii) offshoring could adequately be modeled as a one-time discrete decision; and (iii) offshoring was really aimed at (and achieved) low-cost production.

This section corroborates the paper's main focus (i.e., offshoring as one-shot cost-reduction investment that affected firms' survival and competition) by supplementing the descriptive evidence in section II with selected materials from McKendrick, Donner, and Haggard's (2000, henceforth MDH) book as well as my main data source, *Disk/Trend Reports*. Before addressing each of the three questions separately, I quote part of the beginning paragraphs from MDH's introductory chapter, in which many of the key facts are crystalized.

1. *In 1982, Seagate Technology, a three-year-old HDD startup located twenty miles south of Silicon Valley, began to assemble HDD components in Singapore, becoming the first firm in the industry to do so.* Two years earlier, it had introduced the world's first HDD for the desktop computer. At the time, its main competition was the minifloppy, an inexpensive data storage device that contributed to the explosion in demand for personal computers.

2. *Because potential customers were extremely sensitive to price, Seagate would have to build its new drive cheaply to capture a larger share of the emergent data storage business.* (...) Although competition in the industry was not yet as severe as it would become when more firms entered, Seagate knew that IBM and other computer manufacturers would press relentlessly for lower disk drive prices (...).

3. Seagate made a bold decision. *Not only did it go abroad, but by 1984 it had shifted almost all disk drive assembly to plants it owned and operated in Singapore.* In doing so, the company set in motion a dynamic that, within six years, transformed Singapore into the world's largest HDD assembler.

4. A clutch of other small American disk drive makers followed Seagate's lead. Collectively, these industrial no-names—Tandon, Computer Memories, Maxtor, MiniScribe, Micropolis, Conner Peripherals, Microscience International, and others—completely

upended the industrial status quo. As these small, young multinational corporations (MNCs) pioneered the industry's shift into Southeast Asia, some transformed themselves into large, successful firms. Seagate developed and used its Southeast Asian platform to become the world's largest disk drive producer; the largest private employer in Singapore, Thailand, and Malaysia; and China's largest exporter.

5. While these newcomers were building their base of operations in Southeast Asia, the American industry leaders—IBM, Burroughs, Hewlett-Packard, Memorex, and Digital Equipment—stuck with their existing locational strategy and continued to make disk drives in the United States and Europe. *Not only did the newcomers drive all but IBM from the disk drive industry altogether, they also beat back a challenge from some of Japan's most formidable companies.*

6. Sony, Mitsubishi, Matsushita, NEC, and Hitachi appeared unstoppable in segment after segment of the electronics industry. They nonetheless discovered that manufacturing and exporting disk drives from Japan was no match for (. . .) Southeast Asia. By the mid-1990s, the remaining Japanese majors had moved significant production to Southeast Asia as well, although it was by then apparently too late to challenge seriously the dominance of their American counterparts.[1]

Now, let us delve into each of the three facts.

A.1 Offshoring was the Driving Force of Shakeout

These quoted paragraphs in the above summarize MDH's findings from the wealth of interviews and other qualitative assessments. They group HDD makers into three categories—early, late, and never adopters—and document that the first group prospered at the expense of the latter. Seagate is their primary example, but not the only one.

7. Finis Conner chose to open a Singapore assembly facility because he was aware that an inexpensive cost structure was critical to winning more lucrative high-volume OEM contracts. Thus, with good timing, a good product, and a low-cost assembly location, Conner achieved immediate success: the company became the fastest-growing firm in history, recording $1 billion in sales only four years after its founding. By 1990, it

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[1]MDH, pp. 3–4, emphasis added.

became the dominant disk drive supplier to NEC and Toshiba even though NEC had shipped its first 3.5-inch drive two years earlier before Conner and Toshiba only a few months after ("Conner Peripherals Could Become the Fastest Growing," May 1, 1990). *Although low-cost production in Singapore and later Malaysia was not the only reason for Conner Peripherals' success, it was a necessary condition.*

8. By contrast, in 1983 MiniScribe was "dying on the vinyl," according to its vice president of manufacturing ("Miniscribe's Far East Secret," March 6, 1989). Hit hard when a large customer terminated its contracts, the company made an overnight decision to build drives in Singapore. The decision saved the company, according to the manufacturing vice president. Its Singapore base enabled it to become the top producer of 3.5-inch drives in 1988 and among the top five in 1989. Although the company collapsed in 1990 amid allegations of fraud, it had by then contributed to U.S. leadership in the 3.5-inch market. MiniScribe failed, as have 90 percent of the companies that ever made hard disk drives, but the move to Singapore gave it a four-year lease on life.[2]

MDH also provide further accounts of what happened to Seagate after its initial success, which seem to suggest a potentially larger-scale and longer-lasting impact of offshoring on industry dynamics than product innovations.

9. Seagate, the 5.25-inch pioneer, fell behind Conner, MiniScribe, and the leading Japanese companies in the introduction of 3.5-inch drives and had been missing market windows in the mid-1980s for its 5.25-inch products. (. . .) But once Seagate moved, the huge cost advantage it enjoyed by producing in Southeast Asia quickly enabled it to reestablish a leadership position in this segment. It ranked second in unit shipments by 1988 and became the volume leader in 1991. The company's low-cost, high-quality Southeast Asian base of operations proved an enormous advantage.[3]

This follow-up episode adds important nuances to the role of offshoring in this innovative industry. The transition from 5.25-inch HDDs to 3.5-inch HDDs is a famous episode of product innovation which Christensen (1997) popularized in his best-selling business book entitled *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail.*

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[2]MDH, p. 114.
[3]MDH, p. 114.

Seagate was the top incumbent with 5.25-inch HDDs; Conner was the top entrant with 3.5-inch HDDs. Christensen (1993, 1997) portrayed Seagate as a loser, whereas MDH emphasized its quick come-back thanks to its offshore cost advantage.

According to my own interviews and reading of the data, the truth seems to be in the middle. Seagate's reemergence as the top player in the desktop PC segment had to wait until its merger with Conner in 1996, after the latter ran into financial difficulties due to some unsuccessful investments which were only tangentially related to Conner's main strength. Thus Seagate eventually regained leadership (as MDH highlighted), but only with the acquisition of Conner's strong 3.5-inch products (to the credit of Christensen's thesis).

Regardless of whether we become fans of Seagate or Conner, however, the key fact for this paper is that both of these two top contenders shared the fundamental cost advantage of Singaporean operations, which continued to matter across multiple technological generations. In this sense, I have come to regard offshoring as a larger-scale driving force of industry dynamics than the cycles of product innovations, which was the focus of my previous paper (Igami, forthcoming). As MDH succinctly stated in the above, low-cost production was not the only reason for these firms' successes, but it was a necessary condition. See Online Appendix C.2 (Offshoring and Product Innovation) for more discussions on product innovations.

Figure 1: Seagate's Employment by Country
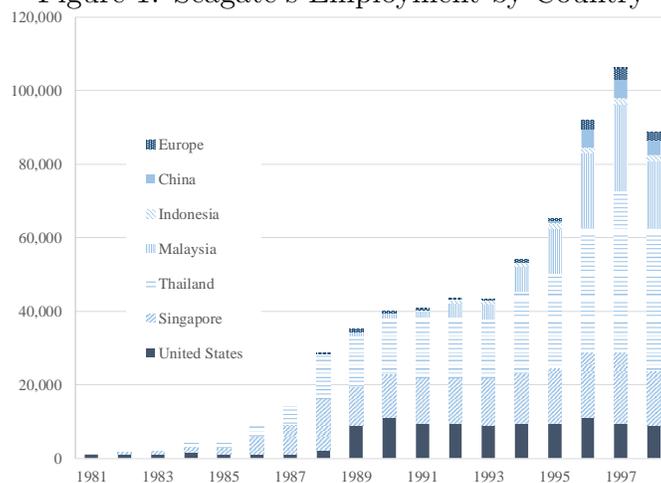
Source: MDH (2000), p. 146, Table 6.10.

Finally, two statistics from MDH further confirm the importance of offshore production in more quantitative manners. The first is the share of HDDs that American firms shipped from South East Asia: 56% in 1983 and 86% in 1987 (p. 111). The second is Figure 1, which

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shows Seagate's historical employment pattern across countries (p. 146, Table 6.10).

A.2 Offshoring as a One-time Discrete Choice

Three types of evidence motivated my modeling decision of offshoring as a one-time discrete choice. First, those who opened new plants in Singapore started volume production there within a year, and typically shut down home-country production within two years. Quotes [1] and [3] at the beginning of this section featured the case of Seagate, which started offshore production of HDD components in 1982, and "by 1984 it had shifted almost all disk drive assembly to plants it owned and operated in Singapore." The following quotes provide more details and other examples.

10. The experiences of Seagate, Tandon, and Computer Memories in Southeast Asia began to influence other American HDD firms. In particular, Seagate's successful Singapore facility spurred several other producers to adopt a similar cost-base location strategy. According to Seagate's president, the company's transportation costs had soared; and communication between U.S. engineers and foreign plants was difficult, as was controlling quality ("Seagate Goes East," March 16, 1987). But company sales jumped from $51 million in 1982 to $222 million in 1983 (its first full year off Singapore-based assembly) and $302 million in 1984, establishing Seagate as the leader in desktop disk drives. Computer Memories also experienced rapid growth, with sales jumping from $41 million in 1983 to $150 million in 1985.[4]

11. Two prominent examples are Finis Conner's Conner Peripherals and Syed Iftikar's SyQuest. Conner, one of the founding members of Seagate, left the company in 1984. (...) Conner then served a brief stint as CEO of Computer Memories, which, like Seagate, was producing drives in Singapore. (...) After a short tenure, Conner left Computer Memories and went on to found Conner Peripherals in 1986. Almost immediately he moved to establish low-cost manufacturing facilities overseas, beginning volume production of disk drives in Singapore in 1987.

12. Syed Iftikar, also a co-founder of Seagate, left the company in 1982 to found SyQuest, just as Seagate made its first investment in Singapore. Soon after establishing SyQuest, Iftikar announced his intention to begin assembling drives in Singapore in 1983 ("The

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[4]MDH, p. 98.

Business Times Reports," March 17, 1984). (. . .) Within two years, half of SyQuest's seven hundred employees were located in Southeast Asia ("Syed Iftikar," June 3, 1991).[5]

Even if some "legacy" facilities in home counties kept operations for a while, their outputs became irrelevant within a year or two anyway, because the demand for computers (hence HDDs) grew exponentially and Kryder's Law (i.e., the doubling of the average HDD capacity every year) constantly pushed existing production capacities into obsolescence, both of which limited the extent to which production adjustments at the intensive margin mattered, especially at the annual data frequency.

Second, MDH and his interviewees use words such as "shifted assembly offshore," "moved (took) production to Singapore," "a dramatic change in the locus of assembly," and "the adoption of a Southeast Asian manufacturing strategy," all of which imply a one-shot, discrete decision akin to technology adoption. By contrast, they never use any phrases that might suggest volume decisions at the intensive margin, such as "adjusted outputs," "gradually increased (decreased) offshore (home) production," or "optimally rebalance capacity utilization rates across plants." Given the nonstationary environment (i.e., the growing demand and the constant advance of technologies), the existing production capacities were almost "perishable," which made "legacy" locations obsolete within a year or two.

Third, industry statistics suggest a rapid shift even at the aggregate level.

13. Virtually all HDD production in 1983 was concentrated in two countries: the United States (72.3 percent of shipments) and Japan (12 percent of shipments).[6]

14. A dramatic change in the locus of assembly took place. Manufacturing in low-cost assembly locations in Asia, particularly Southeast Asia, became the norm among a large proportion of American firms. (. . .) By 1990 Singapore was the world's largest producer of hard disk drives, accounting for 55 percent of global output as measure in unit shipments.[7]

15. By 1990, eight years after the first HDD was produced in Singapore, American firms assembled two-thirds of their disk drives in Southeast Asia.[8]

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[5]MDH, p. 104.
[6]MDH, p. 95.
[7]MDH, p. 98.
[8]MDH, p. 100.

16. By 1995 more than 70 percent of the world's disk drives were produced in Southeast Asia (. . .) HDD production in the United States fell to 5 percent of world shipments (. . .) while production in Japan fell to 10 percent of shipments.[9]

MDH's writing suggests they collected some firms' internal records and based their thesis and numbers on such materials, although their book explicitly reports only a few of them. I do not possess such internal records or systematic plant-level data, but my own interviews and the main data source, *Disk/Trend Reports* (e.g., their qualitative descriptions of plant opening and closure for each firm-year), agree with the characterization of offshoring decision as a one-time discrete choice.

A.3 Offshoring as a Cost-reduction Investment

Virtually every interview and historical account in MDH attests to the fact that both the ex-ante purpose and the ex-post outcome of offshoring were cost reduction. The examples in quotes [2] and [6] epitomize this point. Sections II.B (Offshoring in the HDD Industry), V.B (Results: Marginal Costs), and B.1 (Labor Cost in South-East Asia) present basic facts and discuss my estimates.

MDH report early offshorers' cost calculations as follows.

17. As the largest PC producer, IBM, in particular, had enormous leverage. In 1982, it paid $600 for each 5.25-inch drive it purchased; in 1984 it bought about 1 million 5.25-inch drives at $400 each ("Smaller Business Computers," June 4, 1984). Although some HDD firms did not think such price cuts were sustainable, others were less sanguine. Hoping to lower its operating costs, Seagate was the first to take production to a low-cost offshore location, starting in Singapore with subassemblies in 1982 and final assembly in 1983.

18. Singapore was then a relatively low-wage country with some experience in the manufacture of electronic components. In the early 1980s, for example, its Economic Development Board encouraged U.S. disk drive companies to invest by advertising that an assembly job paying $5 to $6 an hour in California typically pays only $1 an hour in

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[9]MDH, p. 107.

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Singapore. Companies such as Seagate, Computer Memories, and others thus discovered they could reduce the share of labor cost in assembly from almost 25 percent to 5 percent while significantly cutting unit costs.

19. In sum, American disk drive companies increasingly concentrated their technological resources in California, but a handful of pioneers realized they could physically separate volume manufacturing from product and process development. Manufacturing had begun its move offshore.[10]

Note that these numbers are gross savings in assembly wage payments and do not represent net changes to the entire economic costs of manufacturing HDDs. In quote [10], we have already learned that Seagate's transportation and communication costs increased after offshoring, for example. Nevertheless, cost reduction was obviously the main purpose and the effect of offshoring in this industry.

Table 2: Income Statement of Western Digital Corporation (Unit: Million $)

Fiscal year	(1) Revenues	(2) Cost of revenues	(3) Gross profit (margin)	(4) R&D expenses	(5) SGA* expenses	(6) Operating income (margin)	(7) Net income (margin)	(8) Number of employees
1993	1,225	1,043	182 (14.9%)	102	90	−10 (−0.8%)	−25 (−2.0%)	7,322
1994	1,540	1,222	318 (20.6%)	113	113	92 (6.0%)	73 (4.8%)	6,593
1995	2,131	1,737	394 (18.5%)	131	130	133 (6.2%)	123 (5.8%)	7,647

Note: SGA is a shorthand for "Selling, General, and Administrative." According to *Disk/Trend Reports*, Western Digital started its main offshore manufacturing operations at its new factory in Singapore in 1994.
Source: Annual reports.

Accounting information provides another source of cross validation on the magnitude of change in profit margins due to offshoring. Table 2 summarizes Western Digital's financial performance circa 1994, the year in which this HDD manufacturer started operating its new factory in Singapore.[11] Between 1993 and 1994 (or 1995), gross profit margin (column 3)

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[10]MDH, p. 97.

[11]I display Western Digital's financial performances in only 1993, 1994, and 1995, because detailed annual reports are not available for the prior years and the company's financial health deteriorated precipitously in the late 1990s for reasons that are unrelated to offshoring. I have chosen Western Digital for this accounting "case study" because it (1) is a publicly traded firm, (2) specializes in HDDs, and (3) started offshore

improved by 5.7 (or 3.6) percentage points, and so did operating profit margin (column 6) by 6.8 (or 7.0) percentage points. Thus most of the improvements in bottom-line profitability stemmed from the elevated cost-effectiveness at the level of gross profit margin. The magnitude of changes in profit margins closely matches my estimates in the range of 4% to 6% (Figure 3 in section V.B of the main text). This pattern is consistent with the lowering of manufacturing labor costs because these costs enter "cost of revenues" and not R&D or SGA expenses. As an additional piece of suggestive evidence that labor costs experienced structural changes during this period, the number of employees (column 8) exhibits a curious pattern in which it initially decreased by 10% between 1993 and 1994, and then ended up at a higher number in 1995 (4.4% higher than in 1993). Taken together, these changes in profit margins and the number of employees appear consistent with (roughly) synchronous layoffs of high-wage labor in California and hiring of low-wage labor in Singapore. We should keep in mind that accounting profits (in Table 2) are conceptually different from economic profits (in Figure 3 in section V.B of the main text), and that IO economists have largely abandoned the use of accounting data because firms have discretion over how and when to book costs (e.g., "depreciation") and hence "profits." Nevertheless, the extent of cost savings due to offshoring seems surprisingly similar between my estimates and in financial statements, and this fact is reassuring as a ballpark sanity check.

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operations long time after market entry. Other firms are less appropriate for this kind of casual "before-after" analysis because they (1') are privately held firms without public financial records (e.g., many of the smaller players), (2') are conglomerates without HDD-specific financial records (e.g., IBM and most of the Japanese electronics firms), and/or (3') started offshore operations only several years after being incorporated (e.g., Seagate Technology and Conner Peripherals).

B. Additional Descriptive Patterns

B.1 Labor Cost in South-East Asia

Table 3 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 3: 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 MDH (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.

B.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 2 compares the distributions of market shares among home and offshore firms between 1983 and 1998. The unit of observation is firm-year. Three patterns emerge. First, most home firms' market shares are approximately 1%, whereas offshore firms' are typically 3% or higher. Second, a few outliers always exist in a given period, generating long tails with negligible density. Third, because of the shakeout around 1990, everyone's market share grew (i.e., the distributions shifted to the right) in the 1990s, but the overall patterns remain qualitatively similar. I have to acknowledge that, by imposing symmetry among firms producing in the same location, my model misses potentially interesting dynamics of those unique outliers. Nevertheless, these unimodal distributions in Figure 2 suggest my empirical analysis captures the primary difference between home and offshore firms.

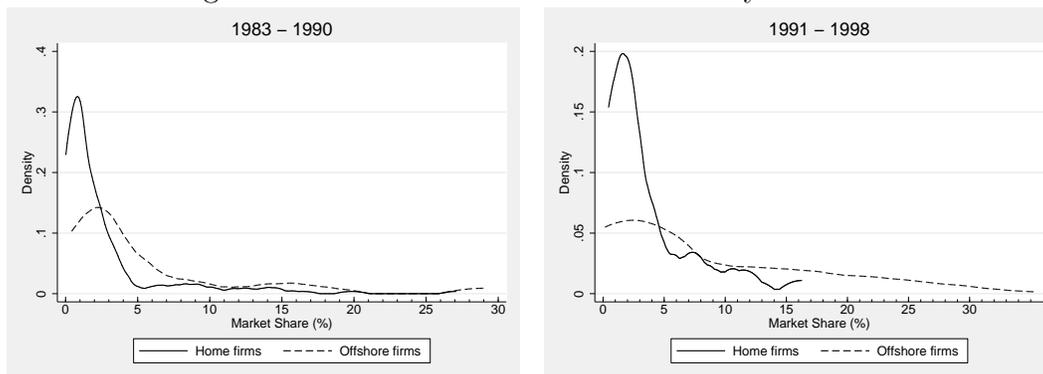Figure 2: Distribution of Market Shares by Location

Figure 3 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.

Another related question is whether more (or less) productive firms self-select into offshoring (or exit). Let us look at Figure 3 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

Figure 3: High Volatility of Firm Size Blurs Persistent Heterogeneity
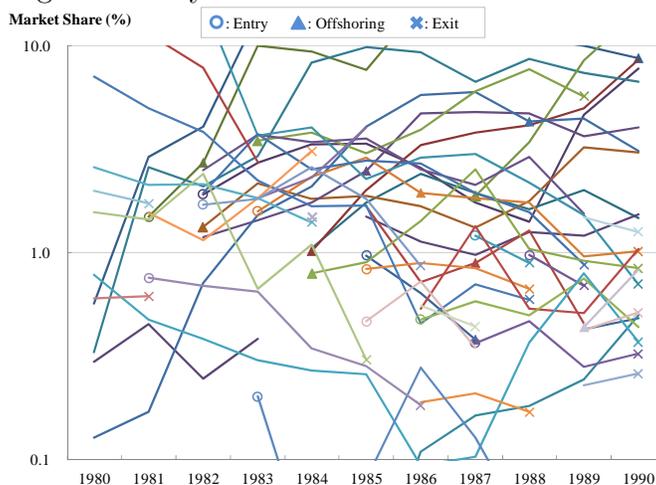
shown in Figure 2 (right) in section II.B of the main text. Likewise, exits (marked by crosses) occur all over the place, showing no clear patterns. Some firms exit despite their respectable market shares, whereas others shrink below 1% and subsequently disappear. The latter trajectory becomes more frequent 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 4 further confirms these impressions, by showing the lack of clear relationships between firms' market share and their propensity to either offshore or exit.

Table 4: 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 V.D 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 6 in Online Appendix C.1).

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B.3 Supply Chain[12]

HDDs are the most complex component in a PC in terms of moving parts. Figure 4 summarizes the supply chain of physical components. Four main components are heads (read/write heads), disks (platters or "media"), motors, and electronics, each of which constitutes a subassembly chain. The outputs of these four subassembly activities are then brought together for final assembly in cleanrooms, and this final process is the main task for HDD manufacturers. One might suspect that final assembly process would not require much technical expertise and that anyone could make HDDs using components from independent suppliers, but such an impression is completely wrong. According to Jeff Burke, vice president of strategic marketing and research at Seagate Technology, "You have to know how to put heads and disks together. You can buy these pieces, but you will have no idea what to do with them. The HDD business is all about the 'magic' of putting them together and make it work, reliably and economically."[13] And offshoring is part of this "magic."

Figure 4: Supply Chain of HDD Components
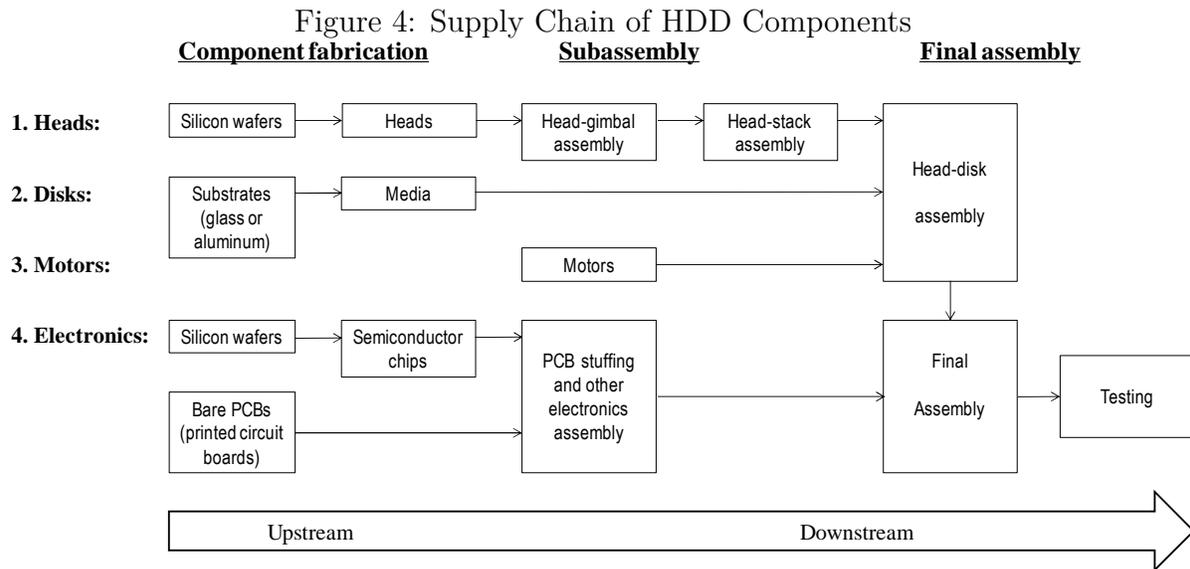
Source: Adapted from Gourevitch, Bohn, and McKendrick (2000) and rearranged by author.

Each HDD maker (i.e., final assembler) takes a different approach in terms of both the extent and scope of vertical integration into critical components, and their approaches changed over time. On the one hand, highly integrated firms such as Seagate, IBM, Fujitsu, and Hitachi made (most of) heads and disks in house. On the other hand, other successful HDD

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[12]Descriptions in this subsection rely on MDH (2000).

[13]Author's personal interview with Jeff Burke at Seagate's headquarters in Cupertino, California, on April 17, 2015.

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makers, including Western Digital and Toshiba, mostly relied on independent component suppliers during the sample period. Table 5 lists some of the major independent suppliers by component category. All of them established their own manufacturing operations somewhere in South East Asia by the end of the sample period.

Table 5: Top Independent Suppliers of HDD Components

| Component	Major suppliers
Heads	TDK (Japan) and SAE Magnetics (its Hong Kong subsidiary); Read-Rite; Alps Electric; Minebea
Disks	Komag, Showa Denko, Mitsubishi Chemical, Hoya
Motors	Nidec, Sankyo Seiki, NMB, NS Habiro
Electronics	Natsteal, Venture, Jabil, Solectron, SCI, Trans-Capital, Tongkah, Sunpino

Source: McKendrick, Donner, and Haggard (2000), *Disk/Trend Reports*.

B.4 Product Diversity

The majority of sales was concentrated in only a few quality levels (capacity in MB) within each generation (Figure 5, 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 5 (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 5: Shipment and Price/MB by Product Category

Industry-wide Market Share

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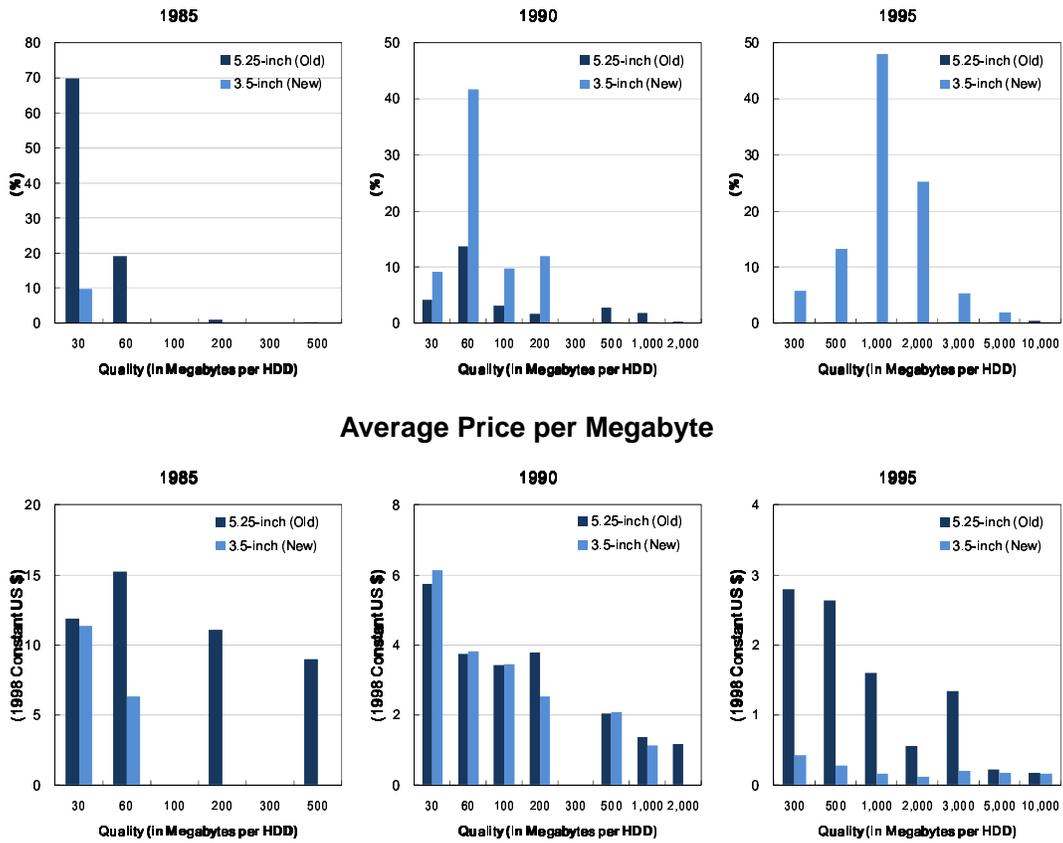
Note: Average prices are calculated by dividing total revenues by shipment quantities. Minor product categories saw few shipments, and hence their average prices are not reliable.

C. Preliminary Regressions with a Duration Model

C.1 Who Offshores and When?

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.[14] Table 6 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 Online Appendix B.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.[15]

This exploratory data analysis treats each firm as an independent decision maker (as in monopolistic competition models) and therefore does not incorporate the endogenous evo-

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[14]For the use of survival analysis in other contexts of international trade, see Besedeš and Prusa (2006), and Obashi (2010).

[15]Both my data and MDH (2000) suggest Japanese firms were slower to offshore than American firms, and their organizational-type compositions seem to play an important role in generating this gap. That is, most of non-American HDD makers (including Japanese) were part of electronics conglomerates, whereas approximately a half of major American makers were HDD-specialized startups. Other, more nationality-based explanations would include the possibilities that languages and other cultural barriers, as well as host-country governments' asymmetric efforts and capabilities in inviting Japanese and American firms.

Table 6: Preliminary Regression of Offshoring Timing on Firm Characteristics

Dependent variable:	Duration model (Cox proportional hazard; *the baseline coefficient = 1*)							
Decision to Offshore	(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 signifiance at the 1%, 5%, and 10% levels, respectively. Standard errors in parentheses.

lution 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 have also incorporated heterogeneous *organizational types* of firms (i.e., specialized versus conglomerate structures) as a sensitivity analysis in the working paper version of this research (Table 4). 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 (forthcoming) for further details on product innovation in the HDD industry.[16]

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[16]See Online Appendix A.3.2 for further investigations into the empirical relationships between offshoring and product innovations, where I found mildly positive but statistically insignificant patterns.

C.2 Offshoring and Product Innovation

The main empirical analysis in section V.B (Marginal Costs) relies on the firm-level data on market shares to infer production-cost advantage of offshore operations based on the premise that HDD products are homogeneous. However, if firms actually gained market shares no by means of lower production costs but by higher-quality products, we would be wrongly attributing the gains from new products to offshore operations. To investigate whether offshoring is positively correlated with product innovation, I report an additional set of offshoring-timing regressions in this section.

Specifically, I constructed two "product innovation" variables from the original data source. The first is "frontier quality," which captures each firm's highest-quality product in terms of data-storage capacity (across all form factors that the firm produces) in each year. The second is "new form factor," which equals one whenever the firm starts manufacturing new-generation products in terms of form factors (i.e., 8-, 5.25-, 3.5-, and 2.5-inch). These two variables represent the two most salient dimensions of HDD product innovations.

Table 7: Offshoring Timing and Product Innovation

Dependent variable:	Duration model (Cox proportional hazard; *the baseline coefficient = 1*)							
Decision to Offshore	(1)		(2)		(3)		(4)	
Firm size$_{it}$	−	(−)	1.000	(.000)	−	(−)	1.000	(.000)
HDD entry year$_i$	−	(−)	.916	(.082)	−	(−)	.924	(.084)
% offshore firms$_t$	−	(−)	18.70	(42.75)	−	(−)	30.59	(71.56)
Product innovation								
Frontier quality$_{it}$	1.065	(.060)	1.092	(.075)	−	(−)	−	(−)
New form factor$_{it}$	−	(−)	−	(−)	1.145	(.488)	1.395	(.630)
Initial tech generation								
8-inch	−	(−)	1.791	(1.284)	−	(−)	1.549	(1.100)
5.25-inch	−	(−)	3.139	(2.271)	−	(−)	2.263	(1.524)
3.5-inch	−	(−)	3.243	(2.790)	−	(−)	2.032	(1.570)
2.5-inch	−	(−)	7.412*	(8.106)	−	(−)	4.176	(4.077)
Organizational type								
Specialized HDD maker	−	(−)	5.361***	(3.072)	−	(−)	5.847***	(3.327)
Computer maker	−	(−)	1.796	(1.121)	−	(−)	1.888	(1.176)
HDD component maker	−	(−)	1.193	(1.364)	−	(−)	1.278	(1.460)
Number of firms	151		151		151		151	
Number of offshoring	42		42		42		42	
Time at risk	772		772		772		772	
Log likelihood	−181.70		−168.33		−182.27		−168.94	

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 signifiance at the 1%, 5%, and 10% levels, respectively. Standard errors in parentheses.

Table 7 reports these offshoring-innovation regressions, using the same template as in Online Appendix C.1. All of the four regressions suggest mildly positive but statistically insignificant relationships between offshoring and the two product-innovation variables. Thus I have come to regard offshoring and production innovation as two orthogonal dimensions of investments.[17]

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[17]Nevertheless, I do not intend to deny the possibility that there can still be some subtle relationships to be uncovered. However, given the inconclusive data patterns in the above and the potential prohibitive computational costs (of explicitly incorporating both offshoring and product-portfolio decisions into the dynamic oligopoly model), I refrain from attempting to write a single paper about "everything that happened in the HDD industry" at this moment.

D. Additional Discussions on the Model

D.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

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

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 6 (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

Figure 6: Strategic Substitutability May Be Reversed in a Dynamic Setting
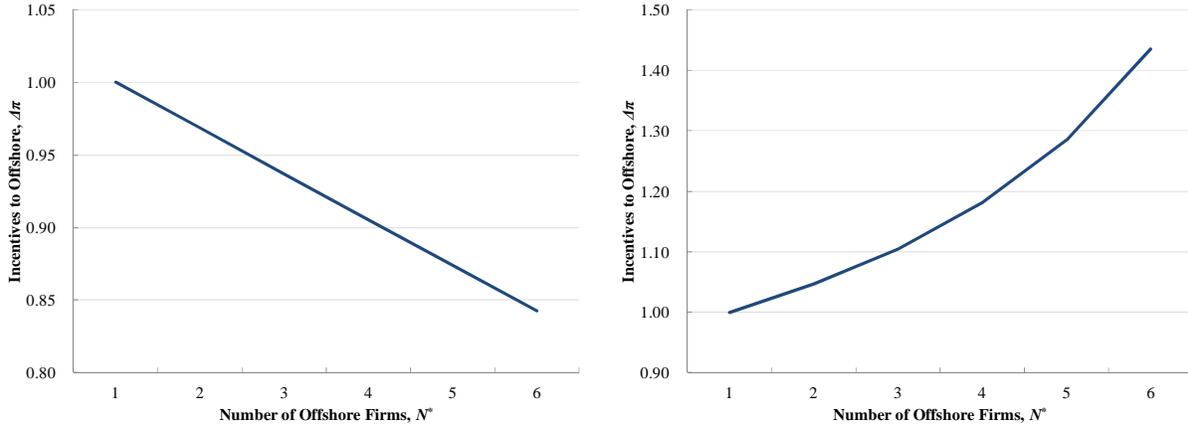
Note: These numerical examples are based on $(mc, mc^*) = (0.09, 0.05)$ and designed for illustration purposes only. The left panel holds fixed the total number of firms at 20, whereas the right panel reduces N by 3 for every increase in N^* to emulate the exit-inducing effect of offshoring. The incremental profits are normalized to one in the baseline state, $(N, N^*) = (19, 1)$.

reduce N more than proportionally. Figure 6 (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 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.

D.2 Uniqueness of Equilibrium

Section III.E (Equilibrium) asserted the uniqueness of equilibrium by listing three key ingredients: (1) i.i.d. private cost shocks to discrete alternatives, (2) sequential moves, and (3) a finite time horizon. This section explains why these features lead to a unique equilibrium.

For ease of exposition, consider a simpler version of the game with a finite horizon in which only one player moves within each period. In the following, we will see that this super-game has optimal substructure and can be solved for a unique equilibrium by dynamic

programming: the principle of optimality.

At $t = T$ in any state s_T, the last player $(i = I)$ has observed all of the past actions by itself and the other players, draws its private cost shocks, $\varepsilon(a_{IT})$, and chooses the highest-payoff discrete alternative, a_{IT}^*, which will completely determine the terminal state of the game, s_∞. Because all of these logit draws are i.i.d. across time and players, their past realizations do not affect I's terminal payoffs, $\pi_{I\infty}(s_\infty)$, hence I does not face any uncertainty after the draw at T. These draws from the continuous distribution rule out the possibility of multiple alternatives with exactly the same payoffs (i.e., the logit draws break ties), hence there will always be one and only one discrete alternative that maximizes I's payoff at T, a_{IT}^*. Thus each of the period-T sub-games has a unique optimal solution.

At $t = T - 1$, in any state s_{T-1}, the second-to-last player $I - 1$ has observed all of the past actions by everyone, and forms rational expectations about the next period, $t = T$. Although no one knows the realization of $\varepsilon(a_{IT})$ at $T - 1$, everyone knows its distribution as well as the optimal choice probabilities that are associated with all of a_{IT}, which follows the usual logit formula (see section IV.C). Thus player $I - 1$ may form the correct belief over the realization of the terminal state, s_∞, which permits the correct calculation of own expected payoffs associated with all states at T, $E\pi_{I-1,T}(s_T)$. And player $I - 1$ is in the position to unilaterally determine s_T by making a discrete choice at $T - 1$. That is, player $I - 1$ draws its private cost shocks $\varepsilon(a_{I-1,T-1})$, and chooses the highest-payoff discrete alternative, $a_{I-1,T-1}^*$, which will completely determine s_T. Therefore, each of the period-$(T - 1)$ sub-games has a unique optimal solution.

In this manner, we may use backward induction to uniquely determine any player i's optimal choice in any period t, conditional on the realization of s_t and $\varepsilon(a_{it})$. Prior to the realization of $\varepsilon(a_{it})$, we (and the players) may use the logit formula to uniquely determine the optimal choice probabilities conditional on the realization of s_t. Let σ_i denote player i's strategy in this alternating-move game with (trivially) private information, which is a mapping from effective state $(s_t, \varepsilon(a_{it}))$ to discrete actions, a_{it}, for all periods in which player i moves. The repeated applications of the principle of optimality in the above lead to the unique profile of all players' optimal strategies, $\{\sigma_i^*\}_{i=1}^I$, that is, a unique PBE (or SE).

Finally, consider a slightly more complicated case in which multiple players of the same types move simultaneously within a period. In general, there can be multiple equilibria in such a game. However, this stage game *à la* Seim (2006) features i.i.d. private information

(ε_i) and a special entry/exit-style structure with payoffs that change monotonically in the action. That is, each player's payoff increases strictly monotonically with its own action (i.e., π_i is strictly increasing in a_i), but the incremental payoff from the action decreases strictly monotonically with the rivals' actions because of product-market competition (i.e., π_i is strictly decreasing in a_{-i} because $\pi(N)$ is strictly decreasing in N, where N is the number of players who entered). Suppose these players are forced to use symmetric strategies and hence the same choice probabilities, then they will end up sharing some intermediate probability of action at which entry is neither attractive nor unattractive ($\Delta\pi = 0$ at a single N^*). Thus, by restricting attention to type-symmetric strategies, I am imposing such symmetry as well as the uniqueness of the choice probability in the stage game.

E. Additional Estimation and Simulation Results

E.1 Estimates of Entry Cost

Unlike ϕ and κ, the two main dynamic parameters, I allow $\{\kappa_t^{ent}\}$ to vary flexibly over time and use the free-entry assumption to bound its sequence, as a by-product of my full-solution estimation procedure. Section IV.C explained this idea, but section V.C did not have enough space to report the estimates, hence I have chosen to display $\{\hat{\kappa}_t^{ent}\}$ in this section.

Figure 7: Entry Cost Estimates
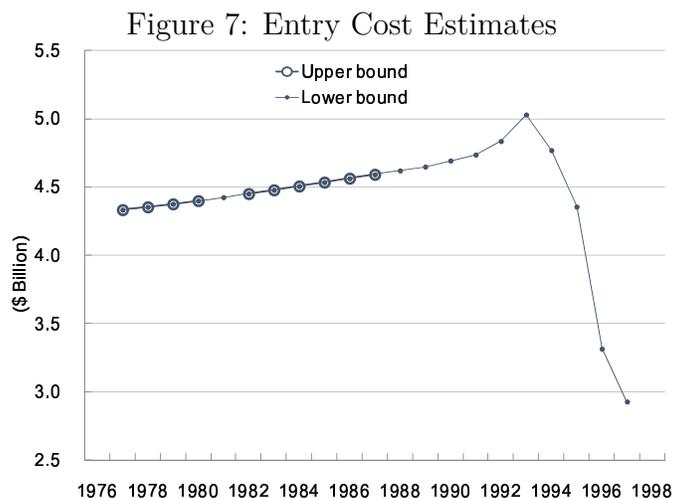
*Note*: See section 4.3 for the construction of this plot.

Figure 7 plots the sequence of entry cost estimates. To be precise, the graph is showing $\hat{V}_t(\tilde{s}_t)$ and $\hat{V}_t(\tilde{s}_t^+)$, the lower and the upper bounds on $\hat{\kappa}_t^{ent}$ (see section IV.C for the notation). These bounds should be different numbers in principle, but their differences are often numerically negligible in practice, because the equilibrium values of home firms quickly converge to some low levels whenever more than five offshore rivals exist. For a concrete example of this phenomenon, see the right panel of Figure 5 (Effects of Market Structure on Profits and Values) in section V.D of the main text. Also note that the upper bounds are available only for years in which entry actually occurred.

E.2 Sensitivity of Simulations with respect to δ

Given the global scope of the HDD industry, the sample size is too small to precisely estimate δ, hence my empirical analysis in section V.C (offshoring cost) calibrates δ, the rate of change of offshoring cost, and Table 5 in section V.C of the main text (Sensitivity Analysis) reports

the sensitivity of the dynamic parameter estimates with respect to δ. This section extends such exercises to assess how sensitive my policy counterfactuals are to the choice of δ.

Figure 8: Sensitivity Analysis with respect to the Growth Rate of Offshoring Cost, δ
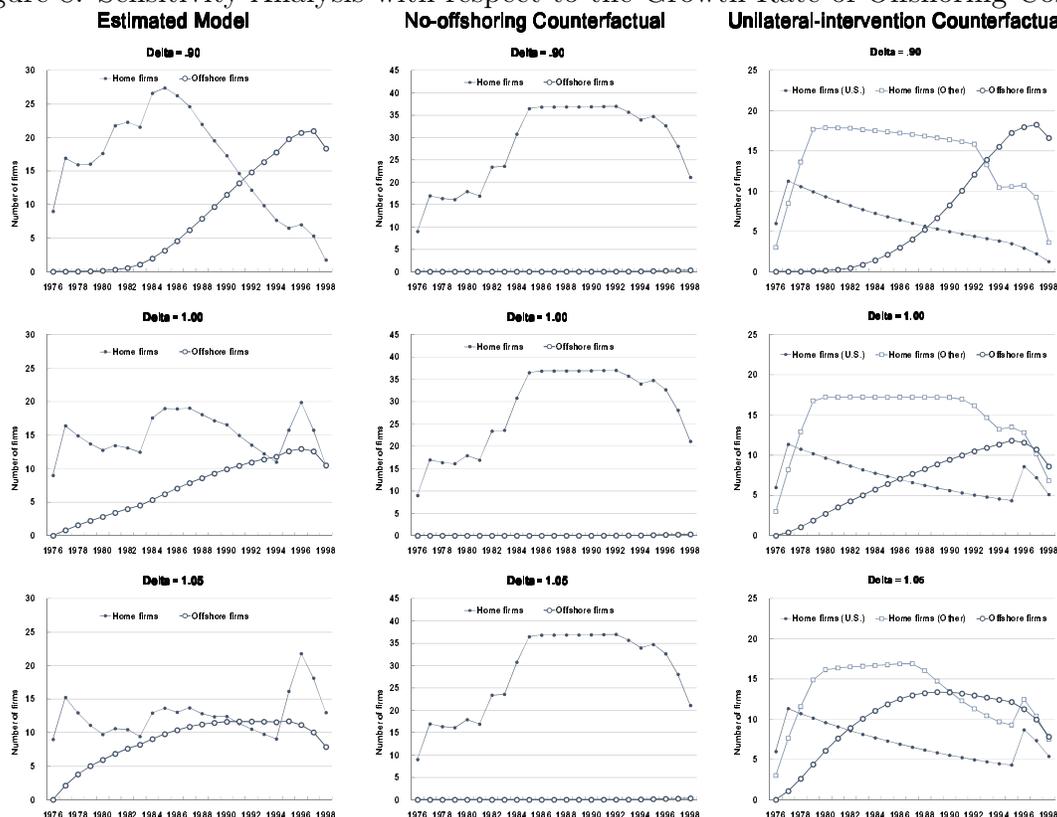
Note: Each graph represents the mean number of firms across 10,000 simulations based on an alternative set of parameter estimates.

Figure 8 presents $3 \times 3 = 9$ graphs to report three simulation results (in columns) based on three alternative values of δ (rows). The first column shows each estimated model's average industry dynamics. The $\delta = .90$ trajectories are similar to the baseline calibration ($\delta = .95$) in Figure 4 (right) in section V.C of the main text. The main difference is that the number of offshoring tends to overshoot both the data and the baseline, because the effective offshoring cost (i.e., $\delta^t \kappa$) becomes very low toward the end of the sample period. By contrast, $\delta = 1.00$ and 1.05 make the effective offshoring cost constant or increasing over time, which incentives firms to offshore early. Early offshoring of some firms, in turn, hasten the onset of shakeout among those who stayed home. Such a head start of offshoring and shakeout becomes so pronounced with $\delta = 1.05$ that even (what was supposed to be) the mass-entry phase at the beginning of the sample period is dominated by shakeout, with the number of active home

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firms (N_t) virtually flat during the first two decades.[18] Thus the main message of the first column is that the baseline calibration ($\delta = .95$) fits the data better than these alternative choices of δ,[19] but some qualitative features of industry dynamics are preserved.

The second column shows the no-offshoring counterfactuals and is a counterpart to Figure 7 (left) in section VII of the main text. The outcomes are virtually identical to each other because, by construction, offshoring cost plays no role in this scenario. This is the scenario in which I set κ so high that $\delta^t \kappa$ is also prohibitively high regardless of δ.

The third column shows the unilateral-ban counterfactuals, which correspond to Figure 7 (right) in section VII of the main text. These simulated histories are qualitatively similar to the one based on $\delta = .95$, but we may find some intuitive differences with respect to the timing of offshoring and shakeout. When the effective offshoring cost declines fast (i.e., $\delta = .90$), the number of (non-U.S.) offshorers overshoots the baseline trajectory (i.e., $\delta = .95$), which wipes out American firms more thoroughly. By contrast (but by the same mechanism), the $\delta = 1.00$ and 1.05 cases feature lower numbers of eventual offshorers, albeit at a faster timing due to the additional preemptive motives.

From these sensitivity analyses, we may conclude that the baseline calibration fits the data the best, but that the insights from the policy counterfactuals are not particularly sensitive to the choice of δ. δ primarily affects the *timing* of offshoring and shakeout in a subtle manner, whereas the policy counterfactuals are designed to alter their overall *levels* by much larger magnitude.

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[18]Under $\delta = 1.05$, the effective offshoring cost becomes prohibitively high toward the end of the sample period. The number of offshore firms stops growing and experiences attrition, which leaves some room to breathe for home firms. This is the reason some potential entrants find entry profitable in the late 1990s, when the releases of Windows 95 and 98 generate windfall profits and an upward spike of N_t.

[19]Note that my maximum likelihood estimation procedure targets the choice probabilities (i.e., actions) and *not* the number of firms (i.e., states) in the data, hence the latter provides an informative measure of fit.

F. Producer Surplus in Strategic Trade Policy

Why are we interested in studying a case in which the governments set the rates of taxes/subsidies on FDI (i.e., offshoring) to maximize industry profit? A short answer is because this specification (i) reflects reality, (ii) captures the core idea of strategic trade policy theory, and (iii) has been studied in the empirical work on political economy.

Fist, let us face the inconvenient truth: "Tariffs are designed to protect domestic firms" (Feenstra 2010, p. 221). For example, the U.S. International Trade Commission's ruling on antidumping cases depends solely on whether imports have caused "material injury" to the domestic industry, with complete disregard for consumer surplus or fiscal revenue (Hansen and Prusa 1995). Feenstra (1989) provides detailed empirical evidence from two U.S. tariffs on imports of Japanese trucks and motorcycles during the early 1980s. U.S. antidumping law even permits the U.S. firm to agree with the foreign firm on the level of prices and market shares (Prusa 1992). This type of communication is illegal under U.S. antitrust law but is exempted from prosecution (Feenstra 2010, p. 213). Evidence is not limited to tariffs and antidumping. Subsidies to production, exports, and R&D investments have been the focus of a "subsidy war" in aircraft manufacturing between the United States and the European Community, which led to a subsidy race between the governments to favor Boeing and Airbus, respectively.[20] Thus the idea that a government maximizes industry profit is normatively outrageous but positivistically relevant.

Second, classic works on strategic trade policy acknowledge the same idea. Brander and Spencer (1985) motivate their theory by saying, "countries perceive themselves as being in competition with each other for profitable international markets." Brander and Spencer (1987) assume national welfare (including consumer surplus, producer surplus, and fiscal revenue) is the government's objective, but only after acknowledging that "it is possible to incorporate 'public choice' considerations (. . .) however, in this paper we restrict attention to the 'public interest' view of government" (p. 266). Indeed, Hansen and Prusa (1995) analyze U.S. antidumping policy based on a model of domestic industry's profit maximization. Regardless of the details, "the general point is that the international marketplace provides strong incentives for unilateral policies aimed at promoting the interests of domestic firms" (Brander and Spencer 1984).

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[20]See Baldwin and Krugman (1988), Irwin and Pavcnik (2004), Benkard (2004), and Kim (2015), among others.

Third, how much domestic industries influence trade policy is an active area of empirical research in political economy. Goldberg and Maggi (1999) estimate a surprisingly high weight on consumers in the U.S. government's implied objective function, whereas Branstetter and Feenstra (2002) found a high weight on state-owned enterprises in China. My paper studies hypothetical policy interventions and not the actual ones, which is why I do not attempt estimating such Pareto weights. Instead, I illustrate two simple examples of noncooperative international equilibria.

My simulation results might appear obvious in hindsight but depend crucially on the structural parameters that govern the benefits and costs of offshoring in a dynamic oligopoly setting. The fact that a dynamic structural reincarnation reproduced the R&D subsidy race (reminiscent of Spencer and Brander 1983) seems to suggest the lasting appeals of this literature.

G. Competitive Shakeout Model

Hopenhayn (1993), Jovanovic and MacDonald (1994), and Klepper (1996) presented models of competitive industry dynamics with shakeout, which suggest strategic interactions are not necessarily the key ingredient to explain shakeout. In this section, I investigate this issue in depth by estimating the Jovanovic and MacDonald (1994) model using my data.

G.1 Non-strategic Models of Industry Dynamics with Shakeout

Jovanovic and MacDonald (1994) is not the only model of competitive shakeout, but I have chosen to estimate it for three reasons. First, it is probably the most prominent theoretical model of shakeout. By contrast, Klepper (1996) is primarily a survey paper that summarizes the author's empirical findings in his past papers. Second, theirs is an equilibrium model with rational, forward-looking firms. By contrast, Klepper's (1996) "model" features myopic firms and other *ad hoc* assumptions that are inconsistent with conventional notions of industry equilibrium. Third, Jovanovic and MacDonald calibrated/estimated the model with data from the U.S. automobile tire industry (1906–73), offering detailed explanations on their empirical approach, the parameter estimates, and the fit, all of which facilitate my estimation exercise. Hopenhayn's (1993) model is richer and might constitute a stronger "straw man" than their model, but I would have to craft an appropriate empirical method of my own to do justice to his model, which is not the primary goal of this section. For these reasons, I will use the Jovanovic and MacDonald model here.

G.2 Jovanovic and MacDonald's (1994) Model

Jovanovic and MacDonald (1994) seek to explain why the number of firms first increases and then falls in a typical industry's life cycle. In their competitive model, a basic invention spawns the industry and fuels entry at the beginning ($t = 0$). Then, at some later point in time ($t = T$), a single major "refinement" of the basic technology becomes available, which attracts more entry. Once this new technology has arrived, all firms try to implement it, but only a fraction r (an exogenously given constant probability of innovation) of them succeeds every year. Successful innovators lower their marginal costs from cq to $cq/\left(1+\theta\right)$ and increase outputs, where q is output, c represents the basic technology, and $(1+\theta)$ is the cost-reduction factor. Those who have failed to innovate keep trying (with the same

success probability r) and some of them would succeed within several years, but eventually the number of new-technology firms reaches certain critical threshold, at which point the downward pressure on the output price becomes sufficiently large to trigger mass exit of those unlucky laggards.

G.3 Estimating the Jovanovic-MacDonald Model

The key parameters of the model are the innovation probability r, the baseline marginal cost c, and the cost-advantage factor θ. Jovanovic and MacDonald's original empirical implementation tries to simultaneously "estimate" these three parameters along with seven other parameters within a single maximum-likelihood procedure. They use a single time-series data from the U.S. car tire industry, $\{(f_t, p_t, Q_t)\}_{t=1906}^{1973}$, where f_t is the number of producing firms, p_t is a wholesale price index for car tires, and Q_t is the industry output.

Identification is dubious in their original empirical implementation, because the model contains ten parameters but the dataset contains only a single episode of shakeout. Consequently, I will focus my estimation efforts only on the most important parameters in my empirical context, and carefully "calibrate" the rest of the parameters. Specifically, my maximum-likelihood procedure estimates c (the baseline marginal cost), θ (the cost-advantage factor), as well as π^a, which is a profit flow from outside the industry and effectively plays the role of the fixed cost of operation in my model (ϕ).

I "calibrate" the other parameter values as follows. First, r (the innovation probability) will be completely determined by the numbers of low-tech (i.e., home) and high-tech (i.e., offshore) firms in my data. Second, (the inverse of) the price-elasticity of demand, d_1, comes from my own demand estimates in section V.A, along with the intercept term, d_0. My demand estimation is independent of my modeling assumptions on the supply side (i.e., the Cournot stage game and the dynamic discrete-choice super-game) and hence can be recycled in this manner. Third, the secular growth of the demand, g, comes directly from my data on the market size (M_t). Fourth, the probability of "refinement," ρ, is specified based on the initial year of offshoring decision in my data, 1982. Fifth, by construction, the probabilities of potential entrants' basic innovation (i.e., entry), (β, r^ϕ), are not separately identified from the measures of potential entrants at time zero and at the timer of refinement, (n_0^ϕ, n_T^ϕ), which are unobserved variables themselves, hence I normalize $(\beta, r^\phi) = (1, 1)$ and set (n_0^ϕ, n_T^ϕ) at values that are consistent with the actual numbers of firms in the data.

Finally, the discount factor, γ, is set at the same baseline level (.8) as in my model. Thus, although I am conservatively calling this part of my procedure "calibration," I minimize arbitrariness by directly connecting all of the parameter values to either my data or my demand estimation results.

Table 8: Estimation and Calibration of the Jovanovic-MacDonald Model

Parameter	Notation[*]	Estimate	Method
Baseline marginal cost	c	0.0077	Main estimate (MLE)
Cost advantage factor	θ	48.228	Main estimate (MLE)
Outside profit when exit	π^a	272.24	Main estimate (MLE)
Innovation probability	r	.0690	Completely determined within MLE
Intercept of demand	d_0	5020.6	From my demand estimates
1/(price-elasticity of demand)	d_1	0.9254	From my demand estimates
Demand growth factor	g	1.2112	From data (market size, M_t)
Refinement hazard	ρ	.1667	From data (initial offshoring year)
Entry probability at $t = 0$	β	1	Normalized (inseparable from n_0^ϕ)
Entry probability at $t = T$	r^ϕ	1	Normalized (inseparable from n_T^ϕ)
Discount factor	γ	.8	Calibrated (identical to my model)

Note: The notation in this section follows Jovanovic and MacDonald (1994) and not mine.

Table 8 shows the estimation results, which suggest a very low marginal cost ($\hat{c} = 0.0077$) and a very large cost advantage of offshore production $\left(1 + \hat{\theta} = 49.228\right)$. These cost estimates could generate unrealistic numbers. For example, the marginal-cost estimate implies variable profit margins in the neighborhood of 50% for home firms in 1982; the cost-advantage estimate implies offshore firms achieved a price-cost margin of 98.43%. In reality, accounting records indicate even the top offshore HDD makers' gross profit margins rarely surpassed 15%, a range that is consistent with my estimates based on the Cournot model in section V.B. Thus the competitive model grossly overestimates the profitability of the HDD business.

G.4 Implications of Assuming Perfect Competition

Why does the competitive model entail unrealistically high profits and equally unlikely cost advantage of offshoring? In other words, why does the model need such parameter values to rationalize the observed pattern of entry, offshoring, and exit? I interpret this result as follows. The competitive model forces individual firms to ignore the negative externalities of competition among themselves. Despite the fact that the total of approximately 20 firms are competing with each other in the homogeneous-good market of HDDs, the assumption of non-strategic competition blind-folds and forces these firms to run in a deadly chicken race.

The only way for such a model to rationalize the presence of 20 firms during the first decade (and the coexistence of high- and low-cost firms during the second decade) is to assume fat profit margins even for high-cost firms.

Another important feature of the Jovanovic and MacDonald model is the assumption of decreasing returns to scale, which is embedded in the upward-sloping marginal-cost functions. This feature is necessary to prevent low-cost (i.e., offshore) firms from immediately taking over the entire market. The model has to rationalize the decade-long coexistence of high- and low-cost firms. At the same time, the model also has to rationalize the eventual shakeout of high-cost (i.e., home) firms after the decade of coexistence. The only way for the competitive model to reconcile these dual mandates is to assume a really big cost advantage of offshore production in the order of $4,823\%$ boost in productivity. This astronomical number is not a unique result that is accidentally caused by the peculiarities of my data or my programming error. Jovanovic and MacDonald's original estimate for theta (in the U.S. car tire industry) is 96.22, or $9,622\%$ productivity growth. The authors attribute this miraculous improvement to the invention of the Banbury mixer in 1916 and its adoption in the subsequent years, which "eliminated the slow, space-intensive, and hazardous process of mixing rubber with other compounds and facilitated large-scale production; in particular, it accelerated the mixing process *by more than an order of magnitude.*"[21] I do not necessarily raise an objection to their interpretation but feel inclined to attribute any extra improvements in estimated productivity beyond "an order of magnitude" to the assumptions of non-strategic competition and decreasing returns to scale.

Figure 9 (left) illustrates the Jovanovic and MacDonald model's fit. The total number of firms increases in 1983 and then decreases in 1993. The sudden nature of entry and exit is characteristic of their model, and their original paper features a similar graph for the car tire industry in their Figure 3(a). These abrupt changes might appear awkward in comparison with the more smooth evolution of market structure in my model (Figure 9, right), but their model is performing exactly what it was designed to do. Thus, although the assumptions of perfect competition and decreasing returns to scale might sit awkwardly with a global high-tech industry, in principle I would not need an oligopoly model if generating this basic entry-and-shakeout pattern were the sole purpose of my research,

However, to fit the Jovanovic and MacDonald model to the entry/exit pattern in my data,

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[21]Hugh Allen, *The House of Goodyear: Fifty Years of Men and Industry* (Akron, Ohio: Superior, 1949), *cit. in.* Jovanovic and MacDonald (1994). Emphasis added by the author.

Figure 9: Comparison of the Models with Perfect and Imperfect Competition
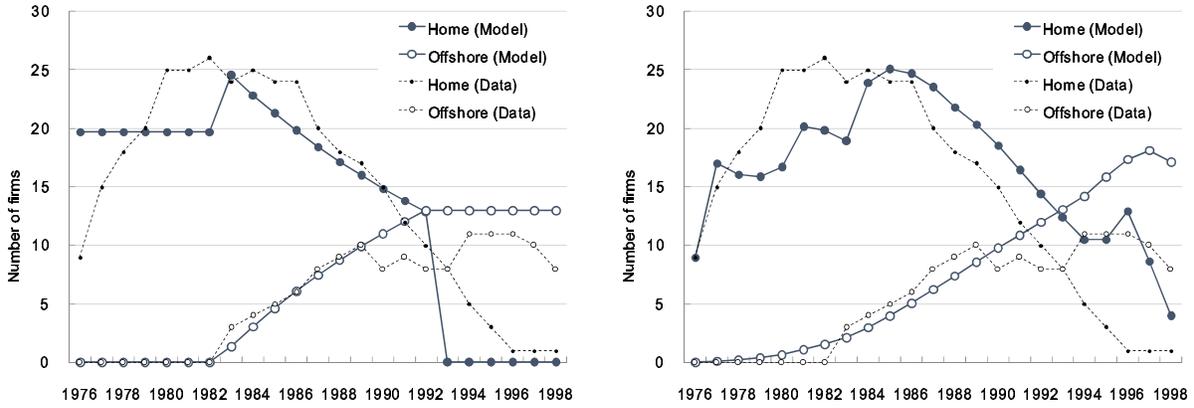
Note: The Jovanovic-MacDonald model generates a deterministic history, whereas my model is stochastic. Thus the right panel represents the mean number of firms across 10,000 counterfactual simulations.

I have to turn blind eyes to its less desirable implications, such as unreasonably high profit margins and an astronomical productivity growth due to offshoring, both of which are fundamental to welfare calculations and policy simulations (see next section). Moreover, I would not be able to investigate the firms' offshoring decisions because their model assumes all firms try to innovate (i.e., offshore) and succeed at an exogenously determined constant probability r. Finally, the assumption of perfect competition shuts down the market-structure dimension and simply assumes away any relationship between offshoring and (imperfect) competition. For these reasons, the purpose of my empirical research necessitates an oligopoly model.

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