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Learning by Doing and Multiproduction Effects over the Life Cycle: Evidence from the Semiconductor Industry

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ABSTRACT

Learning by Doing and Multiproduction Effects over the Life Cycle: Evidence from the Semiconductor Industry

by Ralph Siebert

In this study we derive a structural econometric model of learning by doing with multiproduct competition from a dynamic oligopoly game. We show the importance to account for multiproduction effects through product differentiation when measuring learning by doing. Using quarterly firm-level data for the dynamic random access memory semiconductor industry, we provide evidence that accounting for multiproduction results in lower learning effects and firms behaving more competitive in the product market. We can confirm that firms follow intertemporal production plans for investing in future cost reductions. We also find that learning effects are higher at the beginning of the life cycle.

Keywords: Dynamic Random Access Memory, Dynamics, Economies of Scale, Learning by Doing, Multiproduct Firms, Product Life Cycle, Product Market Competition, Semiconductors, Spillovers.

JEL Classification: L1, L6, O3.

ZUSAMMENFASSUNG

Lerneffekte unter Beruecksichtigung von Multiproduktionseffekten innerhalb des Produktlebenszyklus: Ergebnisse aus der Halbleiterindustrie

Diese Studie untersucht das Ausmass von Lerneffekten unter Beruecksichtigung von Multiproduktionswettbewerb, basierend auf einem dynamischen Oligopol. Der empirische Teil der Untersuchung quantifiziert insbesondere den Einfluss der Produktdifferenzierung auf die Messung von Lerneffekten und Marktmacht.

Auf der Grundlage von Quartalszahlen auf Unternehmensebene aus der dynamischen Speicherchipindustrie, erhalten wir das Ergebnis, dass die Berueksichtigung von Multiproduktwettbewerb in geringere Lerneffekte und einen kompetitiveren Produktmarkt resultiert. Weiterhin zeigen wir, dass Unternehmen dynamische Produktionsplaene beruecksichtigen, um zukuenftige Kostenreduzierungen zu erzielen. Schliesslich koennen wir bestaetigen, dass die erzielten Lerneffekte zu Anfang des Produktlebenszyklus am hoechsten sind.

Learning by Doing and Multiproduction Effects over the Life Cycle: Evidence from the Semiconductor Industry

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December, 2002

Abstract

In this study we derive a stuctural econometric model of learning by doing with multiproduct competition from a dynamic oligopoly game. We show the importance to account for multiproduction effects through product differentiation when measuring learning by doing. Using quarterly firm-level data for the dynamic random access memory semiconductor industry, we provide evidence that accounting for multiproduction results in lower learning effects and firms behaving more competitive in the product market. We can confirm that firms follow intertemporal production plans for investing in future cost reductions. We also find that learning effects are higher at the beginning of the life cycle.

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1 Introduction

Many studies were investigating the phenomenon of learning by doing. Against the background of learning by doing, workers and managers learn from their experiences or improved processes, such that operations become more efficient through reduced time, labor costs, or material waste (see e.g. Dick, 1991; Fudenberg and Tirole, 1983; Majd and Pindyck, 1989; Spence, 1981; and Wright, 1936). Learning is an important market determinant which frequently is considered for government interventions, such as the design of subsidy programs, the promotion of entry and industry growth, as well as antitrust investigations, e.g. the evaluation of setting dumping prices.

The difficulty in measuring learning effects is given by the fact that cost data are often not observable. Most studies attribute firms' production incentives to the measurement of learning effects. This procedure requires to control for firms' production externalities in order to accurately capture the learning effects.

Previous studies, often associated with single product firms, investigate learning effects taking external spillovers between firms into consideration (see e.g. Gruber, 1992; and Flamm, 1993). External spillovers impose positive externalities on rivals' costs, implying that firms may produce less than socially optimal (see Fudenberg and Tirole, 1983).

More recent studies on learning also account for internal spillovers, occurring between different products within one firm. Prominent examples are Irwin and Klenow (1994), Benkard (2000), and Thornton and Thompson (2001). Internal spillovers are due to multiproduction effects on the cost side, e.g. through economies of scope, and exert positive externalities to the firm. This may induce an increase in production in order to achieve further cost savings for other products. The omission of such externalities may result in different production incentives which will be attributed to the measurement of learning effects, resulting in under- or overestimated learning rates.

This study stresses the importance to account for another externality, which is caused by multiproduction effects through product differentiation. Those multiproduction effects, having been neglected up to date, have relevant implications for the measurement of learning effects and market conduct.

Multiproduction effects through product differentiation occur when interrelations between the products exist (see also Anderson, de Palma, and Thisse, 1992).

It is important to account for those interdependencies on the demand and supply side, as it specifies the behavioral response of consumers and firms in a given market. Multiproduct firms take their output decisions at a centralized level such that they control competition effects within their own product line and account for the cross-price elasticities on its other products (see e.g. Bresnahan, 1987; Berry, 1994; Berry, Levinsohn and Pakes, 1995; and Goldberg, 1995). Internalizing those multiproduction externalities has an impact on firms' output decisions. When products are substitutes, firms are aware of the negative externalities which will be imposed on its other products, causing prices to decline. This may induce firms to lower their output.

When accounting for learning by doing and multiproduction effects through product differentiation together, firms output decisions are characterized by the following two opposing effects: (*i*) a higher output achieves higher cost reductions in the future through learning, which induces firms to increase their output, and (*ii*) a higher output causes negative externalities on its other products (in case they are substitutes), which then induces firms to lower their output. As the second effect has been neglected, a smaller production incentive was attributed to the measurement of learning, resulting in an underestimated learning effect.

Moreover, cross-price elasticities may further impact the measurement of learning in an intertemporal dimension. As firms follow a dynamic production strategy, current output will determine future costs and prices through learning. Moreover, as current output also determines future production, future prices of adjacent generations will be affected through the inclusion of cross-price elasticities.

Finally, firms' mark-ups, are determined by market conduct.[1] The higher the competitive degree in the market (lower conduct), the lower the mark-up. Nested marginal costs will be estimated higher, which coincides with lower learning effects. Or in other words, the internalization of externalities on other products caused by cross-price elasticities may capture a (previously omitted) quantity reduction, that results in a higher output response by other firms indicating a higher competitive degree in the product market. The consequence is a lower conduct, which coincides with a lower mark-up. Marginal costs will be estimated higher, resulting in lower estimated learning effects.

The net effect of multiproduct competition through product differentiation on

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[1] The measurement of market conduct has often been analyzed in empirical studies (see e.g. Genesove and Mullin, 1999).

learning, is determined by the interrelation of these aspects: the change in firms' production incentives due to cross-price elasticities and the change in market conduct. A higher estimated competitive degree in the product market may even overcompensate for the larger price-cost margin induced by the inclusion of cross-price elasticities.

A second aspect we concentrate on in this study, is the alteration of learning effects over the product life cycle. Many studies (e.g. Dick, 1991) already claimed that learning by doing (LBD) effects vary over the life cycle, such that LBD effects are higher at the beginning. The gap between dynamic and static marginal costs narrows as the learning effects become smaller at the end of the life cycle (see Figure 1).[2] Hence, firms increase output most during the early stages of the life cycle and may even obtain negative mark-ups by pricing according to their dynamic marginal costs. The fact that LBD effects are higher at the early stages of the life cycle has never been empirically analyzed. Previous empirical specifications modelled the LBD effects as being constant over time. In order to precisely attribute firms' output incentives to learning effects we need to control for the alteration of the learning effects over the life cycle.

We specify a dynamic oligopolistic state-space game using past production experience as the state variable. We derive the supply functions for a multiproduct firm specification with differentiated products and estimate a structural dynamic model of demand and pricing equations. The focus of this study lies on the estimation of market determinants such as learning effects as well as market conduct. Using quarterly firm-level data for the dynamic random access memory (DRAM) semiconductor industry, we estimate the market determinants for a model with multiproduction effects through product differentiation and compare the estimates with a model neglecting those multiproduction effects, a single product firm specification.

The remainder of this study is organized as follows. Section 2 presents the structural characteristics of the semiconductor industry and, in particular, of the DRAM industry. In Section 3, we present the theoretical model of learning by doing with multiproduct firms. Section 4 describes the empirical model. We then turn to a description of the data in Section 5 and present the results. We summarize and conclude this study in Section 6.

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[2] This figure is taken from Dick (1991).

2 The Semiconductor Industry

In the 1980s an extensive policy debate in the United States focused on the semiconductor industry.[3] The discussions centered on the increased competition brought on by the larger number of foreign firms in the United States market, targeting in particular the below-cost sales of Japanese firms. In March 1986, the United States Department of Commerce and the International Trade Commission concluded that Japanese firms set dumping prices for the 64K DRAM chips and other varieties of their semiconductors in the United States.[4]

A considerable number of economic research and policy suggestions have been made with regard to this investigation. Numerous authors have shown that learning has an enormous impact on costs and output decisions.[5] For example, Dick (1991) rejected the dumping hypothesis for the semiconductor industry on the basis that firms follow an intertemporal production strategy, as they will learn in the future from current output. Firms make their optimal output decisions not on the basis of static marginal costs (MC^s) but rather on their dynamic marginal costs (MC^D) which lie below (see Figure 1). Especially at the beginning of the life cycle when learning rates are supposed to be high, prices may fall below static marginal costs.

Many empirical studies find, once LBD effects are taken into consideration, only little evidence that Japanese semiconductor firms engaged in dumping, see e.g. Flamm (1993), Irwin and Klenow (1994). This finding confirms the relevance of accounting for learning effects and their implications for policy decisions.

Semiconductors are mainly used as inputs for the computer industry (45% of its sales), consumer electronics (23%), and communications equipment (13%). The semiconductor market consists of memory chips, micro components, and logic devices. Memory chips (designed for the storage of information in binary form) represent the highest market share (30%). Memory chips consist of DRAM, SRAM, ROM, EPROM, EEPROM, and flash memories. DRAM and SRAM are volatile

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[3] Jorgenson (2001) points out that the semiconductor market is an important industry, as the enormous price decline has been transmitted to product prices that rely heavily on the semiconductor market, i.e. the aircraft, automobiles, and scientific instruments industry.

[4] The United States antidumping laws are included in the United States Trade Agreements Act of 1979, 19 U.S.C. §1673.

[5] For theoretical work in this area see, for example, Wright (1936), Spence (1981), Fudenberg and Tirole (1983), Lieberman (1982 and 1984), and Dick (1991). For empirical work in this industry, see Irwin and Klenow (1994), Flamm (1996), Gruber (1996), and Nye (1996).

memory chips, for they lose memory once the power is switched off. They account for about 90% of the memory chip market. All of the others are non-volatile chips, which do not lose memory (see Gruber, 1996). The DRAM market is characterized by worldwide selling companies from the United States, Japan, Europe, and other countries in the Asian-Pacific region, with a 20.3%, 44.5%, 3.1%, and 32.0% market share, respectively (Dataquest, 1995).

DRAMs are classified into generations according to their storage capacity, which increases by a factor of four. Every generation is a homogenous good in itself, but different generations represent differentiated goods (see Gruber, 1996). The life cycles last for about five years and look very similar to each other. Once a generation is launched, shipments increase enormously and begin to fall when a new generation is introduced. At the industry level, different generations overlap each other (see Figure 2). The same pattern occurs at the firm level, where firms simultaneously produce adjacent generations. For instance, both chips having been under investigation in the United States, the 64K and the 256K chip, are sold by firms that offer at least one further adjacent chip. Focusing on the 64K chip producers, 15 out of 22 produce the 16K DRAM chip, and 19 firms produce the 256K DRAM chip; 12 firms produce even both adjacent generations. Table 1 illustrates the multiproduct firm character for the industry and provides evidence for an oligopolistic industry structure.

The prices for every generation are rapidly decreasing over the life cycles, see Figure 3. The price is high at the beginning and monotonically falls until it bottoms out at the end of the life cycle. The enormous price decline, especially at early stages of the life cycle, is consistent with the notion that learning effects are higher at the beginning.

DRAM chips are produced by etching circuitry design onto wafers of silicon. The manufacturing process is carried out very precisely in terms of temperature, dust, vibration levels, and other determinants. During the production process, firms decrease costs for a given technology by increasing the yield rate and reducing the required amount of silicon material. The yield rate is measured by the ratio of chips that pass the quality test with respect to the above mentioned criteria, and is improved through learning. At the beginning of the life cylce the yield rate often starts at 10% and increases to 90 % at the end of the life cycle (see also Dick, 1991).[6]

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[6] Another aspect of learning by doing is the 'organizational forgetting' hypothesis. With regard to the airline industry, Benkard (2000) found evidence to show that a firm's production experience

Irwin and Klenow (1994) and Flamm (1996) provide evidence that learning is rather limited towards one generation instead of spilling over between different generations. Gruber (1992) noted that *learning enters the manufacturing process through the fine-tuning of generation-specific production processes.*[7] Based on these findings, we abstract from multiproduction effects in costs and concentrate on multiproduction effects through product differentiation.

3 The Model

For the theoretical model, we make our assumptions based on the previous industry description. We shall consider a game similar to that introduced by Jarmin (1994) which is based on Fudenberg and Tirole (1983).[8] A feedback, oligopolistic dynamic game (state-space game) is modelled with n multiproduct firms, indexed by $i = 1...n$, offering subsequent generations $k = 1...K$, in $t = 1...T$ discrete time periods. With state-space games, all past pay-off relevant choices that affect current profits are aggregated into a state-variable for each firm. The current state vector at time period t is described by each firms' cumulative production for generation k, $X_{k,t} = (x_{i,k,t})_{i=1}^{n}$ where $x_{i,k,t} = \sum_{v=1}^{t-1} q_{i,k,v}$ denotes firm i's production experience for generation k, until period $t-1$. We consider feedback strategies in which the information set consists of calendar time and the current state vector. In the feedback structure firms decide on their future strategies at any point in time conditional on their past. In each period of this game, the firms take the current state (past production) and the mechanism for determining future behavior as given. Each firm uses its state-dependent rules to choose current output in each period, with the objective of maximizing the payoff function over the entire product life cycle.[9] Firms take intertemporal effects on

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depreciates over time. Forgetting is crucial in labor intensive industries, but not as important in capital-intensive industries, like the semiconductor industry.

[7] In labor-intensive industries, such as the aircraft and shipbuilding industries, learning is rather characterized by improving workers' and managers' operations.

[8] Related studies are Karp and Perloff (1989) who developed a dynamic feedback oligopoly model that can be used to estimate the degree of market power. Slade (1995) developed a dynamic model in which firms strategies are described by two state variables, prices and advertising intensity. The model is applied for the saltine cracker market. As we focus on multiproduct firms with past production as the state variable, we build on the model by Fudenberg and Tirole and Jarmin.

[9] Feedback strategies are also called closed loop strategies. For a comparison between closed loop and open loop strategies, in which firms precommit towards their production at the beginning

their own and rivals' unit costs in the future through learning into account. A Nash equilibrium in feedback strategies is subgame perfect, when each firm's strategies are optimal at any time t and state, given the other firm's choices. Each firm correctly anticipates how the future actions of its rivals depend on its future costs and on its current output, which prevents firms from making threats they wish not want to carry out.[10]

As we focus on multiproduction effects through product differentiation, we abstract from intergenerational spillovers, which is consistent with the industry, see Irwin and Klenow (1994).[11] Moreover, in order to derive the interdependency between learning and market conduct, we focus on the firm's maximization problem for generation k. Firm i's objective function for generation k, is maximized according to

$$\underset{q_{i,k,t}}{max}\ \Pi_{i,k} = \sum_{t=1}^{T} \delta^{t-1} \left\{ P\left(q_{k-1,t}, q_{k,t}, q_{k+1,t}\right) q_{i,k,t} - C\left(q_{i,k,t}, W_{i,k,t}, X_{k,t}\right) \right\}$$

subject to

$$X_{k,t} = X_{k,t-1} + Q_{k,t-1}, \text{ and } X_{k,0} = 0,$$

where δ is the discount rate and $P\left(q_{k-1,t}, q_{k,t}, q_{k+1,t}\right)$ represents the inverse demand function. As can be seen, the multiproduct effect enters on the demand side, because the market price $P_{k,t}$ not only depends on the total quantity $q_{k,t} = \sum_{i=1}^{n} q_{i,k,t}$ of generation k, but also on the total quantities $q_{k-1,t} = \sum_{i=1}^{n} q_{i,k-1,t}$, and $q_{k+1,t} = \sum_{i=1}^{n} q_{i,k+1,t}$ of the adjacent generations.[12] The industry output vector is denoted by $Q_{k,t-1} = \left(q_{i,k,t-1}\right)_{i=1}^{n}$. Firm i's costs for generation k in period t, given by $C_{i,k,t} := C\left(q_{i,k,t}, W_{i,k,t}, X_{k,t}\right)$, depends on the contemporaneous firm-level output $q_{i,k,t}$, firm-level factor prices $W_{i,k,t}$, the cumulative past output vector, $X_{k,t}$ of its own and of all other firms' experience for generation k until period $t-1$. Hence, firm i learns from its own experience $x_{i,k,t}$ and also benefits through spillovers from its rivals'

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of the life cycle, see Zulehner (2002).

[10] Feedback equilibria are unique, when the equations of motion are linear and the objective functions are quadratic in the state and control variables (see Basar and Olsder, 1991).

[11] Therefore, we assume that the production of generation k is independent of past production of previous generations.

[12] As only adjacent products are simultaneously offered in the market, the cross-price effects to be estimated can be limited towards both adjacent generations.

cumulative past output $\sum\limits_{j\neq i}^{n} x_{j,k,t}$.[13]

We derive firms' first order conditions which are empirically implemented later on. The necessary condition with respect to the quantity of generation k, is given by

$$P_{k,t} + \frac{\partial q_{k,t}}{\partial q_{i,k,t}} \left[\frac{\partial P_{k-1,t}}{\partial q_{k,t}} q_{i,k-1,t} + \frac{\partial P_{k,t}}{\partial q_{k,t}} q_{i,k,t} + \frac{\partial P_{k+1,t}}{\partial q_{k,t}} q_{i,k+1,t} \right] = \frac{\partial C_{i,k,t}}{\partial q_{i,k,t}}$$

$$+ \sum_{s=t+1}^{T} \delta^{s-t} \left\{ \frac{\partial C_{i,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}} + \delta \sum_{j\neq i}^{n} \frac{\partial C_{i,k,s+1}}{\partial x_{j,k,s+1}} \frac{\partial q_{j,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}} \right.$$

$$\left. - \sum_{j=1}^{n} \frac{\partial q_{j,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}} \times \left(\frac{\partial P_{k-1,s}}{\partial q_{k,s}} q_{i,k-1,s} + \frac{\partial P_{k,s}}{\partial q_{k,s}} q_{i,k,s} + \frac{\partial P_{k+1,s}}{\partial q_{k,s}} q_{i,k+1,s} \right) \right\} \quad (1)$$

for $t < s$. The first line shows firm i's marginal profits in a static environment without LBD. It gives the direct effect of firm i's output choice on its profits. The left hand side represents firm i's marginal revenues. The expression $\frac{\partial q_{k,t}}{\partial q_{i,k,t}}$ indicates the conduct parameter (see also Iwata, 1974; and Bresnahan, 1989). A conduct parameter equal to zero refers to perfect competition, where firms behave 'competitively' in the market, whereas a parameter equal to one indicates that firms behave like Cournot players, which coincides with 'softer' behavior.[14] In comparing to the standard marginal revenue term when only one homogenous good is considered in the market (single product firm specification), further cross-price effects $\left(\frac{\partial P_{k-1,t}}{\partial q_{k,t}} \text{ and } \frac{\partial P_{k+1,t}}{\partial q_{k,t}}\right)$ enter the pricing relation. When adjacent products are substitutes (complements),

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[13] For notational convenience and in order to better to distinguish between own learning by doing effects and spillovers, we separate own experience $x_{i,k,t}$, from others' experience $\sum\limits_{j\neq i} x_{j,k,t}$.

[14] In estimating market conduct, Corts (1999) has shown that the identification of market conduct parameters leads to biased estimates when fluctuations in demand are relatively high. The estimated conduct parameter is fully determined by 'equilibrium variation', the extent to which equilibrium quantities respond to fluctuations in demand. Hence, the conduct parameter measures the 'slope' of the price-cost margin with respect to demand variations. The conjectural variations parameter, however, measures the level of the price-cost margin. Consistent estimates of the conduct parameter (in order to accurately measure market power) will provide consistent estimates for the conjecural parameter when the 'marginal' relationship of price-cost margin to quantity is identical to the 'average' relationship of the price-cost margin. As shipments in this industry are rather characterized by smooth movements in demand - rather than high demand and supply shocks when, for example, switching between different competition regimes occurs- this problem is rather minor in this industry.

the cross-price effects are supposed to be negative (positive). The right hand side in the first line represents the common contemporaneous or static marginal costs and indicates how current output affects current costs through economies of scale (ECS).

The following two lines show the dynamic link between firms' current output decisions and firms' environment they find themselves in the future, induced by learning. The term $\frac{\partial C_{i,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}}$ refers to the LBD effect, indicating that own current output increases own experience and yields own cost savings in the future. If LBD effects are present, the term is expected to be negative.

The term $\frac{\partial C_{i,k,s+1}}{\partial x_{j,k,s+1}} \frac{\partial q_{j,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}}$ represents the spillover effect, in which the expression $\frac{\partial q_{j,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}}$ indicates an intertemporal strategic term. The latter expression shows that firm i's output decision in period t increases its experience in the future, having an impact on other firms' future output decisions.[15] The spillover effect measures by how much firm i's costs decline through capturing part of the rivals' experience. The third line of equation (1) shows that future own and cross-price effects enter firm i's pricing relation interacting with the strategic intertemporal term. Therefore, the inclusion of cross-price effects also incorporates an intertemporal impact on price-cost margins and the measurement of learning effects.

As figured out in equation (1), marginal revenues in a multiproduct specification with product differentiation are determined by a further component, the cross-price effects. In order to simplify the following analysis and to focus on the main issue, we will consider the case when adjacent products are substitutes. The cross-price effects have implications for firms' output decisions as they cause negative externalities on adjacent generations. A multiproduct firm takes into account that a higher output of generation k lowers the prices of its adjacent generations. In the presence of learning, the output decisions of multiproduct firms are characterized by a trade-off between increasing the output in order to achieve higher cost reductions through learning effects and lowering the output because prices of adjacent products are negatively affected. In empirical studies, however, observed output is referred to

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[15] The sign of the intertemporal strategic term is ambiguous and depends on the relative magnitude of the LBD and spillover effects (see Jarmin, 1994). When LBD effects are relatively high compared to spillover effects, current output of firm i ($q_{i,k,t}$) and future output of firm j ($q_{j,k,s}$) are strategic substitutes, hence, the intertemporal strategic term will be negative. When spillovers are relatively high, $q_{i,k,t}$ and $q_{j,k,s}$ can be seen as strategic complements and the intertemporal strategic term will be negative.

the measurement of learning effects. Consequently, the inclusion of the cross-price effects, ceteris paribus, results in higher price-cost margins, see equation (1). In our empirical analysis through which a nested marginal cost function will be estimated, it follows that dynamic marginal costs will be estimated lower and learning will be estimated higher, once multiproduction effects are taken into account.

The difference between prices and dynamic marginal costs is also determined by firms' conduct in the market, $\frac{\partial q_{k,t}}{\partial q_{i,k,t}}$. The conduct parameter describes firms' contemporaneous output reactions to firm i's output increase and determines firms' market power. As multiproduct firms are aware of the externalities on adjacent products, a different output incentive might be attributed to market conduct when estimating a multiproduct firm specification with product differentiation. This may result in a more 'competitive', 'identical', or 'softer' estimated market conduct, which impacts the estimate of dynamic marginal costs. For example, a higher competitive degree in the market results in a lower price-cost margin, which is equivalent to the measurement of higher dynamic marginal costs and lower learning effects.

The impact on the measurement of learning depends on the relative magnitude between the cross-price effects and the conduct parameter. In case the conduct parameter is estimated to be more competitive in a multiproduct specification,[16] the larger price-cost margin induced by negative cross-price effects will be overcompensated for by a more competitive market conduct, resulting in lower measurement of learning effects.[17]

We can therefore conclude that multiproduction effects through product differentiation may have crucial implications for learning effects. From the arguments above, we derive the following hypothesis:

> *If market conduct is estimated to be more competitive in a multiproduct firm than in a single product firm specification, learning effects will be estimated smaller.*

In the next section, we test our hypothesis by estimating a structural dynamic model consisting of demand and pricing relations, based on equation (1).

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[16] We may expect that the omitted output reduction (resulting from externalities on neighboring products) results in a more competitive market conduct for the multiproduct firm specification.

[17] When firms behave only slightly more 'competitive' ('identically' or more 'softly'), the smaller conduct parameter will be overcompensated for by the negative cross-price effects. The price-shadow cost margin enlarges in a multiproduct firm specification. Hence, marginal shadow costs will be lower and learning effects will be higher when multiproduct firms are under investigation.

4 The Empirical Model

In order to test our hypothesis, the following structural model will be estimated, having been derived from the theoretical model. The model consists of three inverse demand functions (from which we derive the corresponding own and cross-price effects) and firms' pricing relations, based on equation (1). The latter will be estimated for a multiproduction specification with product differentiation and a single product firm specification. The resulting estimates for learning and firms' market power will then be compared with respect to our hypothesis. We will also control for the alteration of learning effects over the life cycle.

4.1 The Inverse Demand Functions

The inverse demand functions are linear specifications (see also, e.g. Flamm, 1996) given by[18]

$$\begin{aligned} P_{k-1,t} &= a_0 + a_1 * q_{k-2,t} + a_2 * q_{k-1,t} + a_3 * q_{k,t} \\ &\quad + a_4 * q_{k-1,t} * WGDPEL_t + a_5 * t + \varepsilon_{k-1,t} \end{aligned} \tag{2}$$

$$\begin{aligned} P_{k,t} &= b_0 + b_1 * q_{k-1,t} + b_2 * q_{k,t} + b_3 * q_{k+1,t} \\ &\quad + b_4 * q_{k,t} * WGDPEL_t + b_5 * t + \mu_{k,t} \end{aligned} \tag{3}$$

$$\begin{aligned} P_{k+1,t} &= c_0 + c_1 * q_{k,t} + c_2 * q_{k+1,t} + c_3 * q_{k+2,t} \\ &\quad + c_4 * q_{k+1,t} * WGDPEL_t + c_5 * t + \omega_{k+1,t}. \end{aligned} \tag{4}$$

For the sake of convenience, let us consider the inverse demand equation (3) only; the same arguments apply to equations (2) and (4). As can be seen in equation (3), the price $P_{k,t}$ depends on the industry output of the generation under consideration ($q_{k,t}$), as well as the industry output of the adjacent generations $q_{k-1,t}$ and $q_{k+1,t}$.[19] In order

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[18] The specification of the inverse demand functions is in line with the study by Flamm (1996) and Brist and Wilson (1997) in which neighboring generations are specified as possible substitutes. Regarding the robustness of different demand specifications, see Genesove and Mullin (1999). A log-linear specification would cause problems when adjacent generations have 0 shipments.

[19] Note that one chip generation represents a homogenous good in itself, whereas adjacent generations are rather differentiated between each other (see Flamm, 1996; and Irwin and Klenow, 1994).

to avoid identification problems, we account for rotating demand (see Lau, 1982) and add an interaction term consisting of the industry output for the generation under consideration multiplied by $WGDPEL_t$ which refers to the worldwide GDP in electronics and electronical products and is supposed to capture the overall activity in electronics (see Flamm, 1996). The variable is constructed through the production output of the five leading countries selling electronic products, such as the USA, Japan, Germany, France, and the UK.[20] The variable t represents a time trend indicating the length of time a generation has been in the market and corrects for intergenerational "transition" effects (see Flamm, 1996).[21] The expression $b_2 + b_4 * WGDPEL_t$ indicates the own-price effect. The sign is expected to be negative, for a higher output results in lower prices. The parameters b_1 and b_3 refer to the cross-price effects and are supposed to be negative (positive) when adjacent products are substitutes (complements). From the estimation of the inverse demand equations (2), (3), and (4) we obtain the corresponding price effects, given by the estimated parameters $\widehat{a_3}$, $\widehat{b_2} + \widehat{b_4} * WGDPEL_t$, and $\widehat{c_1}$, which are plugged into the pricing relation in the second stage.

Since output is endogenously chosen by firms, we need to use instruments, in order to identify the demand elasticity. As the instruments are supposed to capture the shifts on the supply side, we use marginal cost shifters, summary characteristics of the supply side, that are exogenous to our demand, and exogenous demand characteristics. Those instruments are: price of material (silicon),[22] the number of firms in the market, the Worldwide Purchasing Power Parity - constructed by taking an average of the Purchasing Power Parities of Japan, Germany, France, Italy, and Korea -, the worldwide GDP in electronics, and the age of the generation.[23] The inverse demand functions (2), (3), and (4) are estimated by using the GMM estimator by Andrews (1991 and 1992) which corrects for serial correlation and heteroscedasticity. We assume additive econometric disturbance terms which have a

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[20] These five countries account for more than 90% of the worldwide production in electronics among the OECD countries, which guarantees a good measure for the worldwide GDP. Missing data in the time series data of other countries prevents us from including more than those countries.

[21] The time trend could also be interpreted as a proxy for intertemporal price discrimination among consumers.

[22] In order to explain shifts in the average industry price, we use an world market factor price (silicon) as marginal cost shifter.

[23] The selection of these instruments is similar to Brist and Wilson (1997), which yields robust results.

mean of zero and fulfill the orthogonality condition.

4.2 The Pricing Relations

The pricing relations are derived from the first-order condition in the theoretical model, see equation (1). As described above, price is a function of output and dynamic marginal costs. Firms' dynamic marginal costs are composed of the static marginal costs and the dynamic effects which yield future cost reductions through learning. We begin with describing firms' static marginal costs, approximated by the following semi-log functional form,

$$\begin{aligned}\tfrac{\partial C_{i,k,t}}{\partial q_{i,k,t}} = {} & \alpha_{0,i} + \alpha_1 \ln LBD_{i,k,t} + \alpha_2 \left(\ln LBD_{i,k,t}\right)^2 + \alpha_3 \ln ECS_{i,k,t} + \alpha_4 \left(\ln ECS_{i,k,t}\right)^2 \\ & + \alpha_5 \ln Spill_{i,k,t} + \alpha_6 \left(\ln Spill_{i,k,t}\right)^2 + \alpha_7 \ln MAT_t + \alpha_8 \ln UCC_{i,t} \\ & + \alpha_9 \ln LAB_{i,k,t} + \alpha_{10} \ln E_{i,k,t} + \alpha_{11} \ln FP_{i,k,t} + \eta_{i,k,t} \qquad (5)\end{aligned}$$

where $\alpha_{0,i}$ is a positive firm-specific effect.

For the empirical specification of firms' static marginal costs we take into account that past accumulated output shifts marginal costs through learning. The variables LBD and LBD^2 capture firms' own learning effects; $\ln LBD_{i,k,t}$ measures firm i's experience in production and is constructed by taking the logarithm of the accumulated past production of firm i for generation k until period $t-1$, $\left(\ln LBD_{i,k,t}\right)^2$ is the squared expression and tests whether the learning curve has a different slope over the life cycle. The LBD elasticity $\left(\alpha_1 + 2\alpha_2 \overline{\ln LBD_k}\right) \big/ \overline{\frac{\partial C_k}{\partial q_k}}$ is expected to have a negative sign since a higher degree of experience is supposed to reduce marginal costs.[24] The sign of the parameter α_2 indicates whether the LBD curve is concave or convex. A positive (negative) sign shows that the learning effects are higher (lower) at the beginning of the life cycle.

ECS effects are measured by the variables ECS and ECS^2. These are constructed by using the logarithm of firms' current output of generation k in period t. The overall ECS effect is given by the expression $\left(\alpha_3 + 2\alpha_4 \overline{\ln ECS_k}\right) \big/ \overline{\frac{\partial C_k}{\partial q_k}}$. The sign is expected to be negative, zero, or positive when increasing, constant, or decreasing returns are prevalent.[25] The squared expression ECS^2 captures varying ECS effects over the product life cycle.

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[24] A bar indicates firms' average over time.

[25] Considering both, LBD and ECS effects together, is necessary for both influence each other.

The variables $Spill$ and $Spill^2$ measure the learning effect that firms gain from their rivals' experience through spillovers; $\ln Spill_{i,k,t}$ is constructed by taking the logarithm of the accumulated past production of all other firms for generation k until period $t-1$ divided by the existing number of firms in the market.[26] $Spill^2$ tests if the learning curve, influenced by spillovers, has a different slope over the life cycle. The overall spillover effect is given by $\left(\alpha_5 + 2\alpha_6 \overline{\ln Spill_k}\right) \diagup \overline{\frac{\partial C_k}{\partial q_k}}$. The sign of α_6 is positive (negative) if firm i is able to benefit more from others' experience at the beginning (end) of the life cycle.

We use four different input prices. The variable MAT_t measures the price of material (silicon) and is taken from the 'Metal Bulletin'. The other three input prices are calculated on a firm-level basis. The variable $UCC_{i,t}$ is the firm-specific user cost of capital, which is calculated on the basis of the business reports. For the remaining two factor prices $LAB_{i,k,t}$ and $E_{i,k,t}$ (labor and energy costs), we take into account the international generation-specific production locations for each firm and correct for different factor prices in different countries (production locations). We use the number of different production plants for every firm and every period, in every country. In addition, we use country-specific wages and energy prices. The country-specific factor prices are then weighted with the proportion of plants that each firm operates in every country. The labor costs for firm i, offering generation k in period t, are collected for the semiconductor industry (ISIC 3825) and taken from the *STAN Database*, OECD (1998). The energy prices for firm i, offering generation k in period t, are taken from *Energy prices and taxes*, International Energy Agency/OECD (1998). The parameter estimates of the input prices are expected to have a positive sign since higher input prices increase marginal costs. The variable $FP_{i,k,t}$ captures all other factor prices. Because the firms produce in different countries and the other factor prices vary considerably from country to country, we construct the variable by multiplicatively combining the Producer Price Index with the Purchase Power Parity of each of the countries where production takes place, such as the USA, Japan, Germany, the UK, Korea, and Taiwan. These

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The existence of ECS results in a contemporaneous unit cost decline by increasing output. Ignorance of ECS coincides with an inappropriate omission of the current output variable which impacts the learning effects. The cost reduction effect is exclusively attributed to the learning curve, though part of it is in fact due to the presence of ECS: an omitted variable bias will occur (see Berndt, 1991).

[26] We use the average accumulated past production in the industry, in order to account for the fact that the progress of a technology mainly occurs at the industry or inter-firm level.

indexes are then weighted with the proportion of plants that every firm operates in every country.

As mentioned above, learning also induces a dynamic aspect which yields future cost reductions. For that reason we must account for the fact that firms may price below their static marginal costs in order to achieve future cost reductions. Moreover, we must control for firms' location within the life cycle, in order to capture firms' dynamic production plans over the life cycle.[27] The model would be overparameterized if all terms that measure dynamic effects would be estimated. We enable the estimation procedure through capturing the dynamic effects over the life cycle (equation (1)) as follows, for the multiproduct firm specification (in which own and cross-price effects enter)

$$\begin{aligned}
&\sum_{s=t+1}^{T} \delta^{s-t} \left\{ \frac{\partial C_{i,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}} + \delta \sum_{j \neq i}^{n} \frac{\partial C_{i,k,s+1}}{\partial x_{j,k,s+1}} \frac{\partial q_{j,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}} - \sum_{j=1}^{n} \frac{\partial q_{j,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}} \right. \\
&\qquad \left. \times \left(\frac{\partial P_{k-1,s}}{\partial q_{k,s}} q_{i,k-1,s} + \frac{\partial P_{k,s}}{\partial q_{k,s}} q_{i,k,s} + \frac{\partial P_{k+1,s}}{\partial q_{k,s}} q_{i,k+1,s} \right) \right\} \\
&\qquad = \overline{\alpha}_{12} Fut_{i,k,t} + \overline{\alpha}_{13} \left(Fut_{i,k,t} \right)^2 + \phi_{i,k,t} \qquad (6)
\end{aligned}$$

and the equivalent for the single product firm specification (in which only own-price effects enter)

$$\begin{aligned}
&\sum_{s=t+1}^{T} \delta^{s-t} \left\{ \frac{\partial C_{i,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}} + \delta \sum_{j \neq i}^{n} \frac{\partial C_{i,k,s+1}}{\partial x_{j,k,s+1}} \frac{\partial q_{j,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}} - \sum_{j=1}^{n} \frac{\partial q_{j,k,s}}{\partial x_{i,k,s}} \frac{\partial x_{i,k,s}}{\partial q_{i,k,t}} \frac{\partial P_{k,s}}{\partial q_{k,s}} q_{i,k,s} \right\} \\
&\qquad\quad = \widetilde{\alpha}_{12} Fut_{i,k,t} + \widetilde{\alpha}_{13} \left(Fut_{i,k,t} \right)^2 + \kappa_{i,k,t} \qquad (7)
\end{aligned}$$

where $Fut_{i,k,t}$ represents a firm-specific time trend, indicating how many periods in the life cycle firm i already offers generation k. We also control for varying dynamic effects over the life cycle by including the squared expression. The intertemporal effect is given by $\left(\alpha_{12} + 2\alpha_{13}\overline{Fut_k}\right)$ which is expected to carry a negative sign. The static marginal cost function (equation (5)) and the dynamic effects for the different specification (equation (6) and (7)) will be inserted into the first order condition (equation (1)) of the theoretical model. Solving for the price P gives the pricing

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[27] One alternative might be to apply the method by Pakes and McGuire (1994), see also Ericson and Pakes (1995). As the number of firms in the industry is around 20, this method is difficult to apply.

relation, which we estimate for the multiproduct firm and the single product firm specification.

Multiproduct Firm Specification

The pricing relation for the multiproduct firm specification is given in the following form[28]

$$\begin{aligned}P_{k,t} &= \overline{\alpha}_{0,i} + \overline{\alpha}_1 \ln LBD_{i,k,t} + \overline{\alpha}_2 \left(\ln LBD_{i,k,t}\right)^2 + \overline{\alpha}_3 \ln ECS_{i,k,t} + \overline{\alpha}_4 \left(\ln ECS_{i,k,t}\right)^2 \\ &+\overline{\alpha}_5 \ln Spill_{i,k,t} + \overline{\alpha}_6 \left(\ln Spill_{i,k,t}\right)^2 + \overline{\alpha}_7 \ln MAT_t + \overline{\alpha}_8 \ln UCC_{i,t} \\ &+\overline{\alpha}_9 \ln LAB_{i,k,t} + \overline{\alpha}_{10} \ln E_{i,k,t} + \overline{\alpha}_{11} \ln FP_{i,k,t} + \overline{\alpha}_{12} Fut_{i,k,t} + \overline{\alpha}_{13} \left(Fut_{i,k,t}\right)^2 \\ &-\overline{\alpha}_{14} COND^M_{i,k,t} + \omega_{i,k,t}. \end{aligned} \tag{8}$$

The parameter $\overline{\alpha}_{0,i}$ picks up several firm-specific effects, namely $\overline{\alpha}_{0,i} = \alpha_{0,i} + \widehat{\alpha}_{0,i}$, where $\alpha_{0,i}$ is defined as in the marginal cost function and $\widehat{\alpha}_{0,i}$ is supposed to capture remaining unobserved heterogeneities. The variable $COND^M_{i,k,t}$ represents the expression $\left[\frac{\partial P_{k-1,t}}{\partial q_{k,t}} q_{i,k-1,t} + \frac{\partial P_{k,t}}{\partial q_{k,t}} q_{i,k,t} + \frac{\partial P_{k+1,t}}{\partial q_{k,t}} q_{i,k+1,t}\right]$ (from equation (1)) where the own-price effect $\frac{\partial P_{k,t}}{\partial q_{k,t}}$ as well as the cross-price effects $\frac{\partial P_{k-1,t}}{\partial q_{k,t}}$ and $\frac{\partial P_{k+1,t}}{\partial q_{k,t}}$ will be substituted with the estimated parameters $\widehat{b_2} + \widehat{b_4} * WGDPEL_t$, $\widehat{a_3}$, and $\widehat{c_1}$, respectively, from the inverse demand equation. The parameter $\overline{\alpha}_{14}$ measures the conduct parameter, given by $\frac{\partial q_{k,t}}{\partial q_{i,k,t}}$. Because firms' output is endogenously chosen we need to use instruments. As the instruments are supposed to capture shifts on the demand side, we use the worldwide GDP in electronics, as well as exogenous variables in our model, like number of firms, and firm-level factor prices.[29] We assume additive econometric disturbance terms, which are identically distributed with mean zero and variance Φ. The pricing relation is estimated by using two-stage least squares.

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[28] In order to guarantee that the cost function is well-behaved, we impose a linear homogeneity of degree 1 in input prices, $\overline{\alpha}_{11} = 1 - \sum\limits_{i=7}^{10} \overline{\alpha}_i$.

[29] For a more detailed discussion on regaining consistency when accumulated output is correlated with the error term, see e.g. Olley and Pakes (1996).

Single Product Firm Specification

The single-product firm specification is in line with the multiproduct firm specification, given by[30]

$$\begin{aligned}P_{k,t} &= \widetilde{\alpha}_{0,i} + \widetilde{\alpha}_1 \ln LBD_{i,k,t} + \widetilde{\alpha}_2 \left(\ln LBD_{i,k,t}\right)^2 + \widetilde{\alpha}_3 \ln ECS_{i,k,t} + \widetilde{\alpha}_4 \left(\ln ECS_{i,k,t}\right)^2 \\ &+ \widetilde{\alpha}_5 \ln Spill_{i,k,t} + \widetilde{\alpha}_6 \left(\ln Spill_{i,k,t}\right)^2 + \widetilde{\alpha}_7 \ln MAT_t + \widetilde{\alpha}_8 \ln UCC_{i,t} \\ &+ \widetilde{\alpha}_9 \ln LAB_{i,k,t} + \widetilde{\alpha}_{10} \ln E_{i,k,t} + \widetilde{\alpha}_{11} \ln FP_{i,k,t} + \widetilde{\alpha}_{12} Fut_{i,k,t} + \widetilde{\alpha}_{13} \left(Fut_{i,k,t}\right)^2 \\ &- \widetilde{\alpha}_{14} COND^S_{i,k,t} + \psi_{i,k,t}. \end{aligned} \tag{9}$$

The variable $COND^S_{i,k,t}$ represents the term $\left[\frac{\partial P_{k,t}}{\partial q_{k,t}} q_{i,k,t}\right]$ for the single product firm specification, taken from equation (1). The parameter $\widetilde{\alpha}_{14}$ indicates the conduct parameter given by $\frac{\partial q_{k,t}}{\partial q_{i,k,t}}$. Because the difference between the single product and multiproduct firm specification is given in that cross-price effects do not enter the pricing relation in a single product specification, we only have to substitute the own-price effect $\frac{\partial P_{k,t}}{\partial q_{k,t}}$ with the estimated parameter $\widehat{b_2} + \widehat{b_4} * WGDPEL_t$ from the inverse demand equation.[31] For the estimation procedure as well as for the instruments the same procedure as for the multiproduct firm specification applies.

5 Data and Results

The analysis requires data from a variety of different sources. Some of them have been described already above. The database consists of two different parts. The first part, provided by Dataquest, describes quarterly firm-level shipments and average industry prices for the three different generations beginning in 1974 for the 4K generation and ending in 1996 for the 1MB generation. The second part consists of market characteristics and factor prices which have been discussed above. Summary

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[30] We impose the same restriction as for the multiproduct specification on the cost parameters, which is $\widetilde{\alpha}_{11} = 1 - \sum_{i=7}^{10} \widetilde{\alpha}_i$.

[31] Keep in mind that previous literature followed the same procedure when estimating the single product firm specification. The demand equation has been estimated with respect to adjacent generations, and only the own-price effect was considered inthe pricing relation.

statistics and definitions of the variables used in the estimation are shown in Table 2.

As the pricing relations will be estimated for the 64K DRAM generation (k), we need to estimate the inverse demand equations for the 64K DRAM generation (k), as well as for the 16K DRAM and 256K DRAM generations ($k-1$ and $k+1$, respectively). The estimation results of the inverse demand equations (2), (3), and (4) are presented in Table 3. In the estimation procedures 36, 68, and 57 observations have been used for generations $k-1$, k, and $k+1$, respectively. All three estimations have a remarkably good fit. The adjusted R-squares are 0.70 and higher, and all price-effects but one are significant at least at the 10% level. The own-price effects carry the expected negative sign, indicating that a higher industry output decreases prices. The negative cross-price effects show that adjacent generations represent substitutable products and indicate that a negative externality enters firms' pricing relations in the multiproduct specification. The time trend is negative, which is a plausible outcome, for consumers substitute away from the generation as time passes.

The estimation of the pricing relation for the multiproduct (equation (8)) and the single product firm specification (equation (9)) enables us to test our hypothesis. The estimates are shown in Table 4. In both regressions, 293 observations have been used. A Durbin-Watson statistic by Bhargava, Franzini, and Narendranathan (1982) indicates that the residuals are positively correlated, which we correct for by applying a first order moving average process.[32] Both estimations have a very good fit. The adjusted R-squares for the multiproduct and the single product firm specification are 0.91. The Durbin Watson statistics of 1.70 and 1.74 indicate no further serial correlation. Most of the parameter estimates are significant at the 1% level.

The parameter estimates of LBD and LBD^2 are highly significant for the multiproduct and the single product firm specification. In general, we find evidence that a higher degree of past experience reduces marginal costs in both specifications. Table 5 shows the calculated learning elasticities and learning rates for both model specifications.[33] The learning elasticity for the multiproduct (single product) firm specification amounts to -0.47 (-1.03) which corresponds to a 28% (51%) learning

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[32] Note that the pricing relation is estimated by 2-SLS because a GMM estimation does not converge. The first observation for every firm is being dropped for the correction procedure.

[33] The learning rate is calculated by $1-2^{\alpha}$, where α represents the learning elasticity.

rate. Hence, LBD effects for multiproduct firms are lower than those for single product firms. A doubling in firm's accumulated output (at the sample mean) reduces marginal costs in the multiproduct specification by 28% which is a very reasonable number as it is similar to what has been claimed in the engineering literature. Irwin and Klenow (1994) cite a report by the Office of Technology Assessment (1983) in which the accepted best point of estimate of learning is 28%. In general, the LBD rates reinforce that the model specifications support reliable results.

The parameter estimates for the ECS effects measured by ECS and ECS^2 are shown to be significant under both model specifications (see Table 4). Positive ECS elasticities indicate that decreasing returns to scale are evident (Table 5), which are even stronger decreasing in the single product firm specification. The finding of decreasing ECS effects illustrates the importance of correcting for those, when estimating LBD effects. In contrast, when ECS are assumed to be constant, an omitted variable bias would result in underestimated LBD effects. This phenomenon may also explain why the previous literature under single product firm specification provides lower LBD effects with around 20%-30%, whereas in our study they are estimated to be 51%.

Turning to the estimates of the spillover effects measured by $Spill$ and $Spill^2$ we do not find evident spillovers. The parameter estimates for the dynamic effects, measured by Fut and $(Fut)^2$ in Table 4, are significantly different from zero only for the multiproduct firm specification. Table 5 indicates that the dynamic marginal cost function has an overall negative slope for the multiproduct firm specification. Hence, multiproduct firms follow an intertemporal output strategy in which they increase output today in order to benefit from future cost reductions. They price according to their dynamic marginal cost which lie below static marginal costs. The single product specification does not support intertemporal production effects (see Table 4), indicating that the dynamic marginal cost function is rather flat. Summarizing the facts, results in the dynamic marginal cost function for the multiproduct firm specification lying above those for the single product firm specification.

The estimates for the conduct parameters $COND^{M,S}$ for the multiproduct as well as the single product firm specification are shown in Table 4. A comparison of the conduct parameters supports the claim that a multiproduct firm specification gives different results with respect to market power than a single product firm specification. The conduct parameter for the multiproduct firm specification is close to zero, indicating that firms charge prices close to overall marginal costs and behave as if in perfect competition. In contrast, the parameter estimate for the single product firm model indicates that firms behave like Cournot players. This result is consistent with the previous literature, confirming that the overall model specification gives reliable results. We therefore gain support that firms' behavior is estimated to be more competitive in a multiproduct than in a single product firm specification. As econometricians only know about the observed quantities but not about the unobserved incentive to reduce output - which is due to the internalization of negative externalities on adjacent generations - the omitted externality when specifying a single product firm model leads to an underestimate of the competitive degree in the product market. A multiproduct firm specification controls for the output reduction resulting from internalized externalities on adjacent generations and, hence, results in a more competitive degree of product market competition.

Firm-specific effects are shown to be significant, indicating that unobserved heterogeneities are an important fact for explaining firms' marginal costs. The parameter estimates for the factor prices are all positive (except wages) which is meaningful since higher factor prices are supposed to raise firms marginal costs. User costs of capital, as well as energy prices have a highly significant impact on marginal costs in the multiproduct firm specification. In general, we get relatively similar parameter estimates for the single product and multiproduct firm specification which confirms the functional form chosen for the models and the reliability of the estimations.

Concerning our hypothesis we find strong support for the contention that the learning estimates as well as market conduct are different once we correct for multiproduction through product differentiation. More precisely, we find support for our hypothesis, that market conduct is estimated to be more competitive, and learning effects are estimated smaller in a multiproduct firm specification.

Turning to the alteration of learning effects over the life cycle, we see that the parameter estimate for LBD^2 is significantly positive, indicating that LBD effects are larger at the beginning of the life cycle, an outcome that supports previous assumptions. In investigating firms' dynamic effects over time we provide evidence that the dynamic marginal cost function is convex for the multiproduct firm specification, as shown by the significantly positive sign of $(Fut)^2$ in Table 4. This finding indicates that firms follow an intertemporal output strategy and increase output more at the beginning of the life cycle. The result coincides with higher LBD at the beginning where firms take advantage of the cost reducing effect by increasing production. The significantly positive estimate of ECS^2 indicates that decreasing

ECS effects become even stronger throughout the product life cycle.

6 Conclusion

The purpose of this study is to illustrate the importance of accounting for multiproduction through product differentiation when investigating the measurement of learning effects. One feature that our study highlights is the fact that correcting for multiproduction effects changes firms' objective functions accounting for further externalities between products. Once cross-price effects are accounted for, different output incentives are attributed to the measurement of learning effects.

We find strong support for our hypothesis that adjacent generations are substitutable goods, confirming the notion that negative externalities enter firms' objective functions which are internalized under multiproduct firm specification. A single product firm specification gives that firms behave like Cournot players in the product market, whereas a multiproduct firm specification shows that firms behave more 'competitively' in the product market, as if in perfect competition. Estimating a tougher product market competition corresponds with lower price-cost margins, having an impact on the nested marginal costs and, thus, on learning effects. We find that LBD effects are lower in a multiproduct firm specification with around 28%, whereas in a single product firm specification they amount to 51%. The multiproduct firm specification illustrates the intertemporal effect quite well, that firms follow an intertemporal output strategy and invest in future cost reductions by increasing output.

Putting the findings together, namely, that multiproduct firms behave as if in perfect competition charging prices close to static marginal costs, and also that the average learning rate is about 28%, it follows that the calculated dumping margin of 20% for the 64K life cycle (see Dick, 1991) illustrates quite clearly the finding of marginal shadow cost pricing. We can confirm the result that Japanese firms did not engage in dumping with regard to the 64K DRAM generation, once learning effects are taken into account. However, as opposed to the single product firm specification, we get different results for the degree of product market competition and learning effects in a multiproduction setting. We can conclude that both aspects are very sensitive with respect to multiproduction effects through product differentiation.

Moreover, we provide evidence that learning and ECS effects vary throughout the product life cycle and become smaller over time. The finding of higher intertemporal output effects at the beginning of the product life cycle coincides with higher LBD effects at the early stages showing that firms optimize their intertemporal production plans.

This study demonstrates the importance having regard to multiproduction effects through product differentiation in future investigations on learning. However, the fundamental statement of this study may also apply towards other areas where multiproduction effects play a crucial role and determine firms' behavior in the product market, like for example, mergers, joint ventures, licensing etc.

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Appendix: Figures and Tables

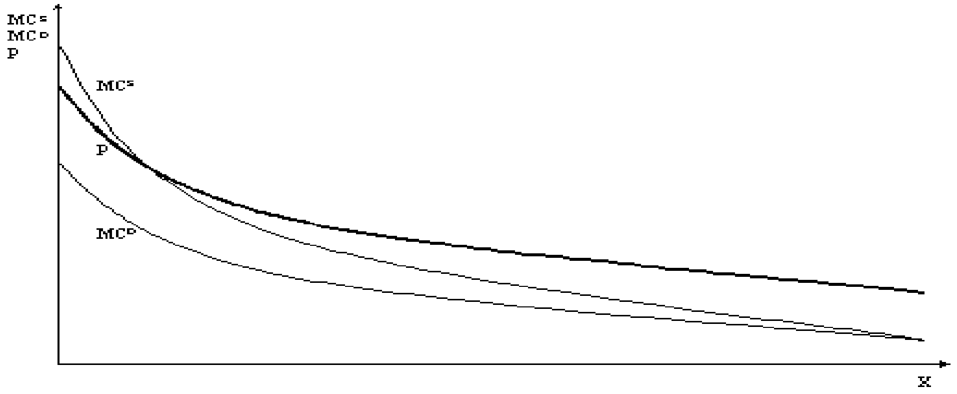

Figure 1: Price setting with respect to shadow marginal costs

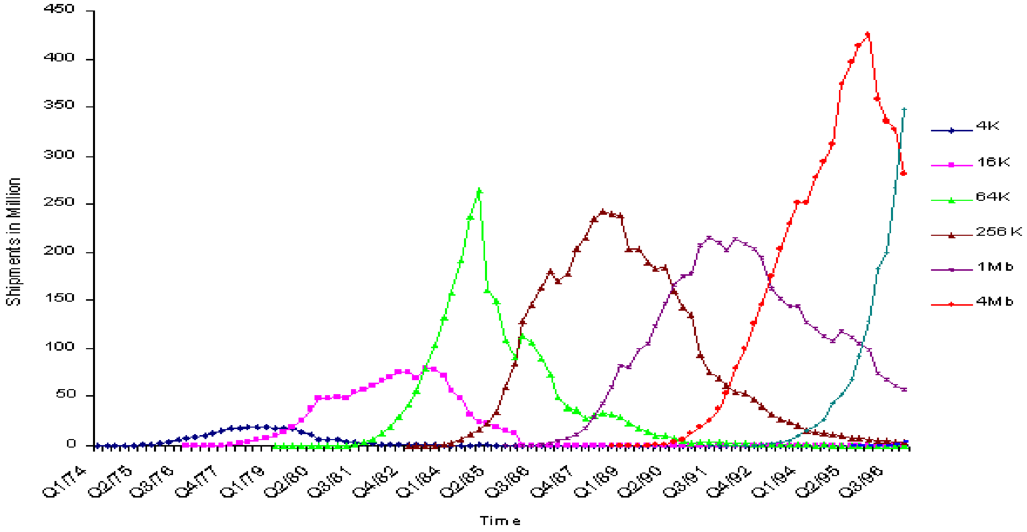

Figure 2: Units of shipments per generation over time (quarterly)

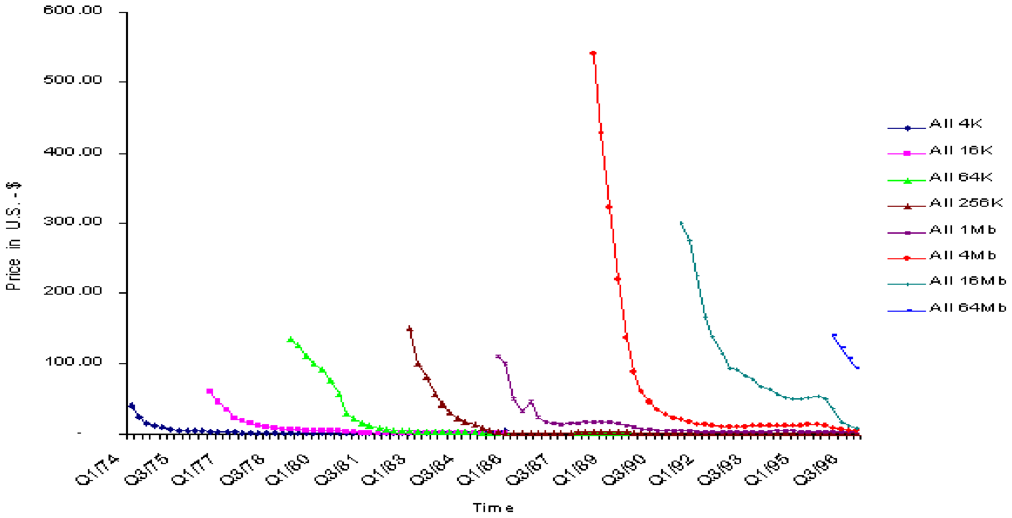

Figure 3: Price decline per generation over time

Firms	Gener.	4K	16K	64K	256K	1Mb	4Mb	16Mb	64Mb
Adv. Micro Dev.	3	x	x	x	.	.	.	.	.
Alliance	1	.	.	.	.	.	x	.	.
Am. Microsyst.	1	x	.	.	.	.	.	.	.
AT&T	2	.	.	.	x	x	.	.	.
Eurotechnique	1	.	x	.	.	.	.	.	.
Fairchild	3	x	x	x	.	.	.	.	.
Fujitsu	8	x	x	x	x	x	x	x	x
G-Link	2	.	.	.	.	x	x	.	.
Hitachi	8	x	x	x	x	x	x	x	x
Hyundai	6	.	.	x	x	x	x	x	x
IBM	4	.	.	.	.	x	x	x	x
Inmos	2	.	.	x	x	.	.	.	.
Intel	5	x	x	x	x	x	.	.	.
Intersil	2	x	x	.	.	.	.	.	.
LG Semicon	5	.	.	.	x	x	x	x	x
Matsushita	6	.	x	x	x	x	x	x	.
Micron	5	.	.	x	x	x	x	x	.
Mitsubishi	7	.	x	x	x	x	x	x	x
Mosel Vitelic	5	.	.	x	x	x	x	x	.
Mostek	4	x	x	x	x	.	.	.	.
Motorola	8	x	x	x	x	x	x	x	x
Nan Ya Techn.	1	.	.	.	.	.	.	x	.
Ntl. Semic.	4	x	x	x	x	.	.	.	.
NEC	8	x	x	x	x	x	x	x	x
Nippon Steel	4	.	.	.	x	x	x	x	.
OKI	5	.	.	x	x	x	x	x	.
Ramtron Int.	1	.	.	.	.	.	x	.	.
Samsung	6	.	.	x	x	x	x	x	x
Sanyo	3	.	.	.	x	x	x	.	.
SGS-Ates	2	x	x	.	.	.	.	.	.
Sharp	4	.	.	x	x	x	x	.	.
Siemens	7	.	x	x	x	x	x	x	x
Signetics	2	x	x	.	.	.	.	.	.
STC-ITT	3	x	x	x	.	.	.	.	.
Texas Instr.	8	x	x	x	x	x	x	x	x
Toshiba	7	.	x	x	x	x	x	x	x
Vanguard	2	.	.	.	.	.	x	x	.
Zilog	1	.	x	.	.	.	.	.	.

Table 1: Multiproduct firms in the DRAM industry

Variables	Description	Mean	Min.	Max.
$P_{k,t}$	Average selling price of one chip of generation k in period t.	13.02	0.75	135.00
$q_{k-1,t}$	Total number of chips of the k-1'th generation being sold in period t.	18.98E06	0	78.54E06
$q_{k,t}$	Total number of chips of the k'th generation being sold in period t.	38.72E06	3000	264.40E06
$q_{k+1,t}$	Total number of chips of the k+1'st generation being sold in period t.	68.62E06	0	242.41E06
$P_{k,t}$	Average selling price of k in period t.	5.55	0.75	100.00
$LBD_{i,k,t}$	LBD for firm i offering generation k in period t.	64.62E06	6000	324.38E06
$ECS_{i,k,t}$	Measure of ECS for firm i offering generation k in period t.	5.05E06	5000	31.53E06
$Spill_{i,k,t}$	spillover measure for firm i offering generation k in period t.	23.21E06	62.80	12.67E08
$q_{i,k-1,t}$	Firm i's number of chips from the k-1'st generation being sold in period t.	1.70E06	0	12.35E06
$q_{i,k,t}$	Firm i's number of chips of the k'th generation being sold in period t.	5.05E06	5000	31.53E06
$q_{i,k+1,t}$	Firm i's number of chips of the k+1'st generation being sold in period t.	2.91E06	0	39.00E06
$WGDPEL_t$	GDP in electronics in period t.	78.61E18	64.05E09	2.18E20
$NOF_{k-1,t}$	Number of firms competing in the market of generation $k-1$ at period t.	4.47	0	17
$NOF_{k,t}$	Number of firms competing in the market of generation k at period t.	14.03	3	20
$NOF_{k+1,t}$	Number of firms competing in the market of generation $k+1$ at period t.	15.75	0	19
$AMS_{k,t}$	Average market share of firms in generation k at period t.	0.10	0.01E-2	1

Table 2: Variable definitions and summary statistics for demand and supply relations

	16K Generation (k-1)		64K Generation (k)		256K Generation (k+1)	
Variables	Estimates	Std. Err.	Estimates	Std. Err.	Estimates	Std. Err.
Constant	100.33**	11.31	134.09**	23.71	208.62**	30.29
q_{k-2}	-2.92E-6**	5.64E-7	-	-	-	-
q_{k-1}	-2.17E-7**	9.17E-8	-6.22E-7**	2.98E-7	-	-
q_k	2.57E-8	4.01E-8	-2.67E-7**	8.01E-8	-5.00E-7**	1.60E-7
q_{k+1}	-	-	-1.47E-7**	6.21E-8	-2.74E-7**	3.01E-8
q_{k+2}	-	-	-	-	-1.22E-7*	6.37E-8
$q_\bullet \cdot$WGDP	-6.99E-21	5.45E-21	-4.70E-21	6.68E-21	6.77E-22	2.07E-21
t	-8.64**	1.36	-6.43**	1.07	-8.91**	1.13
	Obs.=36, adj. R^2=0.73		Obs.=68, adj. R^2=0.70		Obs.=57, adj. R^2=0.74	

**significant at the 5% level, *significant at the 10% level, k-2=4K Generation, k-1=16K Generation, k=64K Generation, k+1=256K Generation, k+2=1Mb Generation.

Table 3: GMM estimates for the inverse demand equations

	Multiproduct Firm Specification		Single-Product Firm Specification	
Variables	Estimates	Std. Err.	Estimates	Std. Err.
LBD	-10.07**	3.13	-8.97**	2.75
LBD^2	0.29**	0.11	0.25**	0.10
ECS	-7.52**	2.36	-12.68**	2.85
ECS^2	0.31**	0.08	0.54**	0.11
$Spill$	-20.42**	1.20	-20.70**	1.17
$Spill^2$	0.61**	0.05	0.63**	0.05
MAT	0.09	0.11	0.06	0.11
UCC	0.78**	0.25	0.79**	0.25
LAB	-0.05	0.15	0.002	0.15
E	0.12*	0.07	0.09	0.08
$COND^{M,S}$	0.25*	0.16	1.09**	0.39
Fut	-19.40*	10.64	-14.69	10.66
Fut^2	17.06*	9.07	13.20	9.06
$\alpha_{0,1}$	300.54**	16.91	323.10**	19.55
$\alpha_{0,2}$	290.64**	16.51	312.67**	19.07
$\alpha_{0,3}$	300.89**	15.89	324.58**	18.95
$\alpha_{0,4}$	298.26**	15.81	322.13**	18.92
$\alpha_{0,5}$	303.08**	17.81	324.52**	20.10
$\alpha_{0,6}$	299.69**	16.52	322.67**	19.30
$\alpha_{0,7}$	297.39**	16.28	320.78**	19.18
$\alpha_{0,8}$	298.27**	16.55	321.46**	19.37
$\alpha_{0,9}$	299.70**	16.30	323.37**	19.27
$\alpha_{0,10}$	298.39**	15.95	321.96**	18.95
$\alpha_{0,11}$	303.28**	16.65	326.22**	19.40
$\alpha_{0,12}$	304.28**	16.34	324.10**	18.46
$\alpha_{0,13}$	298.40**	15.97	322.06**	18.97
$\alpha_{0,14}$	295.69**	16.28	318.86**	19.15
$\alpha_{0,15}$	302.14**	17.42	324.95**	20.06
$\alpha_{0,16}$	301.79**	16.43	325.06**	19.28
$\alpha_{0,17}$	303.16**	17.05	326.23**	19.78
$\alpha_{0,18}$	300.59**	15.51	324.41**	18.64
$\alpha_{0,19}$	299.59**	16.07	322.92**	19.00
$MA(1)$	-0.53**	0.06	-0.52**	0.06
	Obs.=293, adj. R^2=0.91, DW=1.70		Obs.=293, adj. R^2=0.91, DW=1.74	

**significant at the 1% level, *significant at the 10% level, $\alpha = \overline{\alpha}$ for multiproduct firm specification and $\alpha = \widetilde{\alpha}$ for single product firm specification.

Table 4: Pricing relation

	Multiproduct Comp.		Single-Product Comp.	
Effects	Elast.	Rate	Elast.	Rate
LBD	-0.47	28%	-1.03	51%
$Spill$	0.19	/	0.49	/
ECS	1.32	/	2.47	/
Fut	-16.46	/	-12.42	/

Table 5: LBD, spillover, ECS, and intertemporal effects

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