Innovation and the Creation, Development and Destruction of Markets in the World Machine Tool Industry

Axel Wieandt

ABSTRACT. In the 1970's the Japanese machine tool builders began to create and develop, first in the US and later in Europe, new markets for computer-numerically controlled (CNC) machine tools. Their control-technology innovations rendered the machines of their US competitors obsolete. Consequently, many US and German machine tools builders, who saw their markets being destroyed by their larger Japanese competitors in the late 1970's, were forced to exist the industry in the mid 1980's. This study identifies the main characteristics of the world machine tool industry, describes the evolution of the world machine tool industry from the early 1960's, and analyzes the effect of Japanese innovation on US and German machine tool markets.

A. Introduction

I. *Purpose of this study*

In the 1970's the Japanese machine tool producers began to create and develop new markets for computer-numerically controlled (CNC) machine tools in the US. Their control-technology innovations rendered the machines of their US competitors obsolete. Many US machine tool builders, who say their markets being destroyed by their larger Japanese competitors in the late 1970's were forced to exit the industry in the mid 1980's. The European markets which were traditionally dominated by German machine tool builders are the next target of the Japanese.

An analysis of the development of the world machine tool industry is a good starting point for a more theoretical analysis of the market and industry structure effects of innovation. Therefore, the purpose of this study is

— to identify the main characteristics of the world machine tool industry,
— to describe the evolution of the world machine tool industry since the early 1960's, and
— to analyze the effect of technical innovation on machine tool markets and industry structure.

This study takes a global perspective on the machine tool industry. It is focused on three countries: the US, Japan and Germany.

II. *Methodology*

This study relies on the following two types of sources:

— research papers and books published on the subject and
— production, export and import figures, and other industry data published by the American Machinist, the US National Machine Tool Builder's Association (NMTBA),[1] the Japanese Machine Tool Builder's Association (JMTBA)[2] and the German "Verein Deutscher Werkzeugmaschinenfabriken e.V." (VDW).[3]

This study attempts to combine time-series and market share analysis with a qualitative assessment of the evolution of machine tool technology, especially control technology.[4] In the theoretical part, it tries to blend a competitive strategy view on innovation and markets with the industry structure implications of Sylos-Labini's oligopoly theory[5] and its most recent extension by Phlips (1980).

III. *Procedure*

Part B defines the terms 'market', 'industry' and

Final version received August 16, 1993

WHU Koblenz
Vallendar, Germany

Small Business Economics **6**: 421–437, 1994.

'innovation' and presents the theoretical framework used to analyze the developments in the world machine tool industry. Part C describes the evolution of the world machine tool industry. It identifies the main characteristics and trends of the machine tool industry (section I) and presents a global market share analysis for the period from 1964 to 1990 (section II). Part D takes a closer look at the concomitant evolution of machine tool technology. It describes the evolution of control technology in three steps: Numerical control (NC) (section I), computerized numerical control ((C)NC)[6] (section II) and direct numerical control (DNC) that allows the integration of several machine tools and peripherals into a flexible manufacturing system (FMS) (section III). Part E uses the theoretical framework of part B to analyze the findings of part C against the background of technological change as described in part D. It will be shown how the sunk costs of creating and developing markets for a new technology reinforce sunk production cost barriers to entry and thus add to the industry structure effects of innovation. Finally, part F summarizes the major findings and concludes the study with suggestions for further research.

B. Theoretical framework: The creation, development and destruction of markets through innovation

I. *Markets and industries*

A market is defined as a bundle of transactions between the firm and its customers. This market definition suggests that the market is not a given institution as implicitly assumed by neoclassical theory but rather the outcome of the firm's strategic decisions to engage in transactions with certain customers. Abell distinguishes between three strategic dimensions of a market transaction: the identity of the customer ('customer'), the technology embodied in the product ('technology') and the customer function or application ('function') which is served by the product (Abell, 1980, p. 169). Exploring these three dimensions involves sunk (information) cost commitments in terms of market research, R&D and advertising. These sunk costs can be considered endogenous because they are incurred based on a firm's strategic decision;[7] the firm does not necessarily take cost and demand as given but tries to act on both to gain a sustainable competitive position. An industry consists of firms with similar but not necessarily perfectly overlapping market definitions and common underlying core products and production technologies. Intentional trade can be regarded as the manifestation of competition between national industries for market share in the aggregate world market.

II. *Innovation*

In this study innovation is defined "as the introduction into the market of a 'new' physical product [and]/or of a 'new' technological production process, based on invention and development" (Albach, 1991, p. 1). The notion of innovation is a subjective one. A transaction is considered an innovation if at least one of the three attributes of a transaction is new to the supplying firm.

III. *The creation, development and destruction of markets through innovation*

There are considerable barriers to innovation. They are mainly of an informational nature. To successfully create a new market, the innovating firm must collect, combine and act on information about customers' functional needs and its own technological means. This task is further complicated by problems of information asymmetry and technological uncertainty that cause additional transaction cost. The more effectively and efficiently the internal and external communications networks operate, the better a firm is equipped to create and make markets. Setting up and running on internal and external communications network involves significant amounts of sunk cost. A large portion of these information costs are independent of the number of new products sold. This leads to economies of scale.

If the firm manages to sell a new product — embodying a new technology and/or serving a new customer function — to a new customer, *a new market is created* (Wieandt, forthcoming). After this successful 'first-to-market' transaction, in order to recoup its up-front sunk investments in market research, R&D and advertising, the firm must intensify its market relationship by selling more products to the same customer and/or try to expand its market by selling to other customers. The more easily an innovation can be imitated the faster the innovating firm must try to recoup its up-front sunk investments. Barriers to entry are typically lower than barriers to the creation of markets because of the positive demand and production externalities of any innovation.

New markets need not necessarily be created by established firms. They can also be created by start-up ventures or by joint ventures between start-up and established companies. The entrepreneur founders of start-up ventures are often in a better position to combine means and need information than large organizations. Moreover, the incentives to innovate are usually higher for independent entrepreneurs than for members of a large corporate organization.

Similarly, the firm can *develop its markets* by introducing into existing transaction relationships a product based on a new process technology and/or with a new functional application. Continuous technological up-grading of the transaction relationship is the best defense against the threat of substitutes. Typically, the barriers to market development are lower than the barriers to market creation because in market development the supplier can build on the experience and reputation gained from established customer relationships. Such an innovation strategy is less risky because it involves smaller amounts of sunk investments. However, returns will be smaller because other firms that innovate on the same technological path will be able to imitate and follow in a relatively short period of time.

Innovation can also *destroy markets*. This can happen through vertical integration. Vertical integration is warranted if technological innovation has increased the firm and market specificity of a product or service to the extent where the market transaction cost becomes higher than the cost of internal coordination.[8] It can also happen through a process of substitution. If a market is created and customers wander away from an established market to this new market the former is gradually destroyed. In this case, market destruction is the flip-side of market creation. Ultimately, the creation, development and destruction of markets are the outcome of dynamic competition.

IV. *Dynamic competition and industry structure*

1. *Innovation and industry structure*

Most of past theoretical and empirical research has been concerned with the impact of market structure on innovation. The results of theoretical research on the relationship between innovation and industry structure are ambiguous. Schumpeter had developed the hypothesis that innovation increased with concentration in an industry (Schumpeter, 1987). According to his hypothesis, the incentive to innovate is associated with the expectation of ex post market power, and profits derived from the possession of ex ante market power provide the firm with the internal financial resources necessary to invest in innovative activity. Fellner (1951) and Arrow (1962) have argued on the contrary that the firm's gains from innovation at the margin are larger in an industry that is competitive ex ante than under monopoly conditions. Scherer (1980) has argued that insulation from competition in a concentrated industry breeds bureaucratic inertia and discourages innovation. Phillips (1966) was the first to reverse the causality. He holds that "success breeds success" and therefore innovation increases industry concentration. His case study of the civilian aircraft industry presents conclusive evidence of this reversed causality (Phillips, 1971). More recent studies take into account the simultaneity between innovation and industry structure.[9] Overall, however, the empirical results concerning the relationship between industry structure and innovation must be considered "fragile" (Cohen and Levin, 1989, p. 1079). The only conclusive finding seems to be that the relationship between innovation and industry structure is highly sensitive to industry conditions. Individual industries differ with regard to three different dimensions:

- product market demand,
- technological opportunity, and
- appropriability conditions.

The first two dimensions describe the strategic leeway firms have to influence demand and cost conditions by sinking funds into market research, advertising, and R&D. If firms do not chose to create new markets but rather try to develop existing markets the growth rate of demand and demand elasticities become important determinants of the innovativeness of an industry. Higher price elasticities favor process innovations (Kamien and Schwartz, 1970), and lower price elasticities favor product innovations (Spence, 1975). However, since both types of innovation often occur together, the expected rate of market demand growth becomes the important determinant. The third dimension describes how easily firms can recoup their up-front sunk cost investment.

2. *Sylos-Labini's oligopoly theory and its implications for industry structure*

2.1. *Limit pricing.* A good starting point for the theoretical analysis of the relationship between innovation and industry structure is Sylos-Labini's oligopoly theory (Sylos-Labini, 1969). It is simple and intuitive and allows us to establish a link between the theory of innovative behavior of the individual firm and industry structure. While the limit pricing part of the theory has been well integrated into the industrial organization literature on barriers to entry the implications of this theory for the relationship between innovation and industry structure seem to have been neglected. They were, however, equally highlighted in Modigliani's famous review article (Modigliani, 1958).

Sylos-Labini analyzes the situation of a homogenous oligopoly that faces the threat of entry. He tries to determine the maximum long-run entry-preventing price that the incumbents can change in a given industry. In order to come up with a stable equilibrium solution he assumes that the incumbents will maintain output after entry.[10] The incumbents are assumed to behave as Stackelberg price leaders and the potential entrants act as Cournot followers. If economies of scale are large and entry is only possible at the minimum efficient scale X the entry-preventing quantity and price are determined by the following equations:

$$X_o = X_c (1 - 1/S), \tag{1}$$

and

$$P_o = P_c (1 + 1/\eta S), \tag{2}$$

where X_c and P_c are the competitive output and price respectively, η is the elasticity of demand and $S = X_c/X$. P_o tends to increase with the importance of economies of scale and to decrease with the size of the markets and the price elasticity of demand. In a heterogenous oligopoly, economies of scale are increased by "the selling costs involved in acquiring an adequate circle of customers."[11] If economies of scale are less pronounced and small scale entry is thus possible, P_o is lower and X_o is larger than in the larger-scale entry case. Therefore, equation (1) defines the lower bound on P_o and equation (2) defined the upper bound on X_o.

2.2. *Implications for the relationship between innovation and industry structure.* Sylos-Labini's limit price theory implies that firms that are smaller and therefore less efficient than the largest firm in the industry can survive and prosper under the umbrella of the limit price P_o as long as their long-run average costs do not exceed this price. Thus the possible range of the scatter of firm sizes in an industry depends on the determinants of P_o. The range will tend to be greater the smaller the economies of scale, the size of the markets, and the elasticity of demand. Industry structure tends to be more stable in a heterogenous oligopoly where there exist technological opportunities for product innovation to meet customers' specifications. Large firms will find it profitable to serve only the largest markets in an industry, leaving it for the smaller firms to produce for the smaller, less profitable markets. If the large firms wanted to serve the speciality markets with their commodity products, they would have to lower their price on their products by more than the incremental value of the speciality to the customer. The profits to be gained in these markets, however, would not compensate for the price-induced revenue losses in the larger markets unless the firm could perfectly price discriminate between the two markets.[12]

What happens if the there is the opportunity for a combined product and process innovation? On the one hand, a technological change that quickly spreads throughout the industry has little impact on industry structure. As the long-run average cost of all firms are lowered P_o will fall but market shares will remain fairly stable. If the change in long-run average cost is not too drastic the optimal full cost mark-up will remain almost stable. On the other hand, a combined product and process innovation that can be kept proprietary for while by a certain (group of) suppliers(s) — be it through patents or through quick exploitation and superior marketing — will have considerable industry structure effects. Information cost will magnify existing economies of scale. The falling limit price will force a reduction in mark-ups. The least efficient firms will be forced to exit the industry and the profitability of the speciality firms will be considerably reduced. This concentration effect can be cushioned by a simultaneous increase in demand (that leaves more room for less efficient firms) or reinforced by a simultaneous fall in demand.

2.3. *Phlips' extension.* Phlips (1980) offers a dynamic extension to Sylos-Labini's limit-pricing theory. He models the incumbent firms as choosing the optimal price in an intertemporal framework. In particular, he shows that in an intertemporal framework normal costing will lead to decision rules that are compatible with firm and industry equilibrium. Normal costing can explain price stickiness and the building up of inventories. Unlike Sylos-Labini who assumes the threat of entry to be certain Phlips incorporates a modified version of Kamien and Schwartz's probabilistic approach to the threat of entry into his model (Kamien and Schwartz, 1971). Under this approach the probability of entry h is a function of the prevailing entry price p(t); h(p(t)) is also referred to as the hazard rate.

Phlips' modelling results in a comprehensive linear equation, that links price p to the intercept of the demand function α, average normalized marginal cost k and the loss due to the threat of entry ψ dh/dp dp/dq.

$$p = [1/(m+\gamma)]\,\alpha + [m/(m+\gamma)]\,k - [\gamma m/(m+\gamma)\psi\ dh/dp\ dp/dq. \quad (3)$$

The parameters of this linear equation are a function of the number of firms m and the cooperation coefficient γ, with

$$\gamma = (1 + \Sigma\ \delta qj/\delta qi) > 1;\ \text{firms } i = 1, \ldots, j. \quad (4)$$

This equation has several implications for the relationship between innovation and industry structure. For a given market structure, an increase in global demand has a smaller impact on the price than an increase in the average marginal cost of production evaluated at the normal level of output. This effect is weakened if firms in the industry cooperate. In more concentrated industries, changes in demand are more fully transmitted into prices and cost increases are less fully transmitted into price than in less concentrated industries. These effects are reinforced if firms in the industry cooperate. Barriers to entry reduce the threat of entry and therefore have a positive impact on prices. The better the cooperation among firms, the stronger is the positive impact of the barrier-to-entry variable on price.

In comparison with Sylos-Labini's approach, Phlips' theory seems to gain its analytical compactness at the expense of two drawbacks. First, it does not allow us to analyze innovation as a strategic decision of the individual firm. It only analyzes the impact of industry-wide changes in technology on the industry price level. Second, it relies on conjectural variations. Sylos-Labini (1969, p. 54) explicitly tried to ban conjectural variations from his oligopoly theory and wanted to explain industry price as determined only by "objective elements".[13]

2.4. *Emerging hypotheses.* The following broad hypotheses emerge from our discussion of the relationship between innovation and industry structure:

As an individual firm or a cooperating, fairly homogenous group of firms quickly exploits a competitive advantage based on product innovation and economies of scale and scope (process innovations)

- their market shares will increase at the expense of the non-innovating firms;
- the overall industry price level will be lowered; the effect on price can be cushioned by a concomitant increase in demand (parallel shift of the demand curve); it can be reinforced by a concomitant fall in demand; and
- the smaller firms will be forced into smaller niche markets; their profitability will decrease and the least efficient firms will gradually be forced to exit the market.

The more firms exit the market and the more concentrated the industry becomes, the more sensitive prices will be to demand shifts. In what follows, it will be argued that the evolution of the world machine tool industry over the last 25 years has followed a pattern that is consistent with these hypotheses.

C. The evolution of the world machine tool industry since the mid 1960's

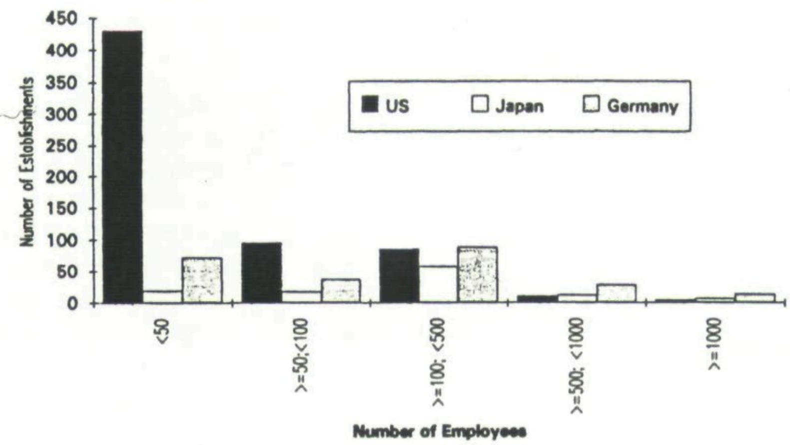
I. *Characteristics of the world machine tool industry*

A machine tool is usually defined as "a power-driven machine, not hand-held, that is used to cut, form, or shape metal."[14] This study is only concerned with the core of the machine tool industry which comprises metal-cutting and metal-forming machine tools. Boring machines, drilling machines, milling machines, grinding machines, lathes and machining centers are typically referred to as metal-cutting machine tools. Die casting machines, presses, punching machines, shearing machines, bending machines, folding machines, straightening and flattening machines and forging machines are typically classified as metal-forming machine tools. In 1990, 76.4% of the total world machine tool production was metal-cutting machine tools (American Machinist, 1991, p. 36).

The machine tool industry is one of the smallest sectors of the manufacturing industry in most industrial countries. If the entire US machine tool industry was ranked by its 1989 shipments, it would be listed no higher than 132nd on the Fortune 500 of top companies by sales. In Japan, metal-cutting machine tools represent only 1.7% of the 1989 production value of the machinery and equipment industry (VDW, 1990). In Germany, machine tool sales represented only 1.13% of total 1989 manufacturing sales (Payne and Sciberras, 1985, p. 83). In all three countries the machine tool industry is essentially a small firm industry as Figure 1 shows.

The machine tool industry is very heterogeneous. There are many different types and sizes of machine tools. Payne and Sciberras (1985, p. 19) classify the products of the machines tool industry along four dimensions. First, they distinguish between general purpose machines and special purpose machines. General purpose machines are characterized by their flexibility. Special purpose machines are geared towards the mass-production of specific parts and pieces. Second, depending on the extent to which the machine tools are built from standardized components, they distinguish between standard and custom engineered machine tools. Third, they draw a distinction between systems and stand-alone machine tools. Finally, they classify the machine tools by control technology, distinguishing between conventionally and numerically controlled (NC/CNC) machine tools.

In spite of its small size and heterogeneity, the



Sources: US: Census of the Manufacturers 1987;
Japan: JMTBA (1989 JMTBA members only);
Germany: VDW (1989 members only).

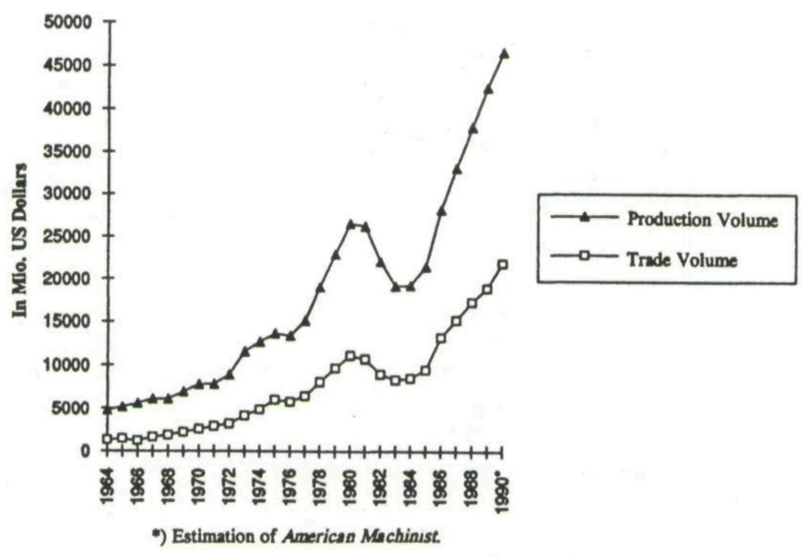
Fig. 1. Size Distribution of Machine Tool Builders in the US (1987), Japan (1989) and Germany (1989).

machine tool industry is a strategic industry. Few, if any products or services of an industrialized country, would exist without machine tools. Production of automobiles, airplanes, home appliances, power plants, and most other products would be impossible without machine tools. According to Carlsson (1989, p. 246) "the machine tools industry may be regarded as a "node" for supplying both hardware and software to all metal-working industries, thus playing a crucial role in determining the performance of large sectors of manufacturing in terms of both productivity and international competitiveness".[15]

In general, machine tool builders spend little on formal R&D. Payne and Sciberras (1985, p. 83) report the overall level of formal R&D to be around 1 to 2% to turnover in the US, Japan and Europe.[16] This figure tends to underestimate the R&D efforts of machine tool builders in the custom segment where most of the development efforts appear as engineering expenses of specific custom designs. Most of the key technological developments, however, have occurred outside the machine tool industry as the evolution of control technology exemplifies.

The machine tool manufacturing process is characterized by high capital intensity. In fact, machine tools are also used to manufacture machine tools. Most of the demand for machine tools emanates from a few key manufacturing sectors such as automotive manufacturers and aerospace. These customer industries tend to have strong cyclical swings in their investment patterns. Therefore, orders for machine tools are typically related very closely to the business cycle. Actual production of machine tools is also closely related to the business cycle because machine tool builders are not willing to bear the cost of idle investments during economic downturns. Likewise, the strong demand cyclicality leaves the machine tool builders unable to sustain internally financed R&D programs over the long run.

Trade has traditionally played an important role in the industry. This importance has increased during the last 25 years. In 1964 total exports accounted for 28% of total world production. By 1990 this percentage had risen to almost 47% (see Figure 2). So far, the degree of foreign direct investment in the world machine tool industry has been low (O'Brien, 1987, p. 24). Recently, however, Japanese machine tool builders have increased their foreign direct investments to the US and Europe following the Japanese automotive industry (Boston Consulting Group, 1990).



Sources: *American Machinist*, various issues; own calculations.

Fig. 2. Rising World Production and Trade (in Mio. US Dollars), 1964—1990.

II. *Production and trade analysis*

The following production and trade analysis will be performed in two steps. First, overall machine tool production and trade will be analyzed. It is shown that the US machine tool industry has virtually collapsed while the Japanese machine tool industry has moved into dominance and the German machine tool industry has been able to sustain its competitiveness in the custom segment. Second, this development is further analyzed by taking a closer look at the markets for NC machine tools, especially numerically controlled (NC) multi-functional machining centers and NC lathes.

1. *Changing distribution of world output and trade*

World machine tool production has risen steadily since World War II (see Figure 2). In 1964, the total value of the world machine tool production amounted to 4.7 billion US dollars. By 1990,

TABLE I
Shifts in global market shares: US, Japan and Germany, 1964—1990

(in Mio. Dollars)	1964	1970	1975	1980	1985	1990[a]
US						
Production	1194,3	1443,1	2364,9	4812,3	2717,8	3140
(in % of world production)	(25,1%)	(18,5%)	(17,3%)	(18,1%)	(12,6%)	(6,7%)
Exports	285,7	305,1	567,6	734,1	452,4	1060
(in % of world trade)	(21,2%)	(11,6%)	(9,4%)	(6,6%)	(4,8%)	(4,9%)
Imports	35,8	131,8	317,6	1259,8	1738,5	2340
(in % of consumption[b])	(3,8%)	(10,4%)	(15%)	(23,6%)	(43,4%)	(52,9)
Exports/Imports	8,0	2,3	1,8	0,6	0,3	0,5
Japan						
Production	304,6	1109,4	1059,9	3830,3	5316,5	10832,1
(in % of world production)	(6,4%)	(14,2%)	(7,8%)	(14,4%)	(24,8%)	(23,2%)
Exports	17,9	90,9	313,3	1452,9	2179	3996,6
(in % of world trade)	(1,3%)	(3,5%)	(5,2%)	(13,1%)	(23%)	(18,3%)
Imports	63,2	160,6	145	221,1	219	640,8
(in % of consumption	(18,1%)	(13,6%)	(16,3%)	(8,5%)	(6,5%)	(8,6%)
Exports/Imports	0,3	0,6	2,2	6,6	9,9	6,2
Germany						
Production	757,6	1479	2399,5	4707	3168,4	8826,5
(in % of world production)	(15,9%)	(18,9%)	(17,6%)	(17,8%)	(14,8%)	(18,9%)
Exports	390	800,4	1827,1	2797,6	1806,6	5159,1
(in % of world trade)	(28,9%)	(30,6%)	(30,4%)	(25,2%)	(19,1%)	(23,6%)
Imports	129	212,5	219,6	776,4	586,1	2113,4
(in % of consumption)	(26%)	(23,8%)	(27,7%)	(28,9%)	(30,1%)	(36,6%)
Exports/Imports	3,0	3,8	8,3	3,6	3,1	2,4

Sources: *American Machinist*, various issues; own calculations.
[a] Preliminary data.
[b] Consumption = Production + Imports − Exports.

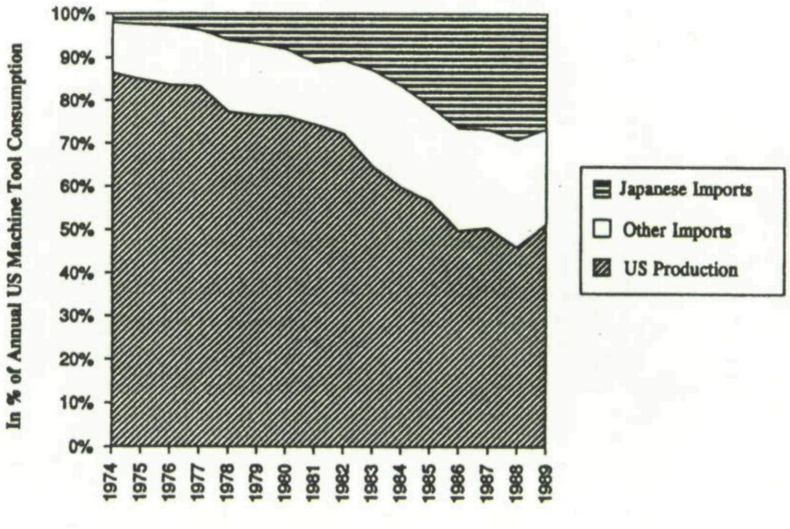
despite a much weaker US currency, that amount has increased by a factor of almost 10 to 46.6 billion US dollars. This (nominal) growth has been accompanied by dramatic shifts in market shares (see Table I). In 1964 one quarter of the world's machine tools were manufactures in the US. By 1990 that share had declined to a mere 6.7%. Most of the ground lost by the US has been made up by Japan. Today almost one quarter of the world's machine tools are being manufactured in Japan.

In 1978 the US turned from a net exporter of machine tools into a net importer of machine tools. The US has lost a large portion of its home market to the Japanese machine tool industry (see Figure 3) as Japan has turned from a net importer to net exporter of machine tools.

As the US machine tool industry has declined and the Japanese machine tool industry has skyrocketed, the German machine tool production has grown in unison with world production. In 1990 it accounted for 18.9% of the world machine tool production (compared Table I). The German machine tool industry has traditionally been export oriented. In 1990 it is still the world's leading export nation (see Table I). However, unlike Japanese imports, German machine tool imports have grown with the increase in exports as the relatively stable export/import ratio in Table I confirms. This suggests that Germany relies more on global division of labor than Japan. As will be discussed in part E, the German machine tool industry has managed to defend its leadership in custom engineered machine tools while giving away the markets for standardized machine tools to Japanese imports.

2. *Numerically controlled machine tools: Creation, development and destruction of markets through innovation*

What caused these changes in market shares? Further analysis suggests that the shifts in market shares have been caused to a large extent by innovation.[17] The Japanese have successfully managed to *create new markets through innovation.* They have found new customers all over the world, many of them in the US, for their NC machine tools thereby *destroying most of the domestic markets* of machine tool manufacturers. The Germans, on the contrary, seem to have managed to *develop their markets through innovation.* They have kept their traditional customers while adapting their custom engineered machine tools to the new control technology.



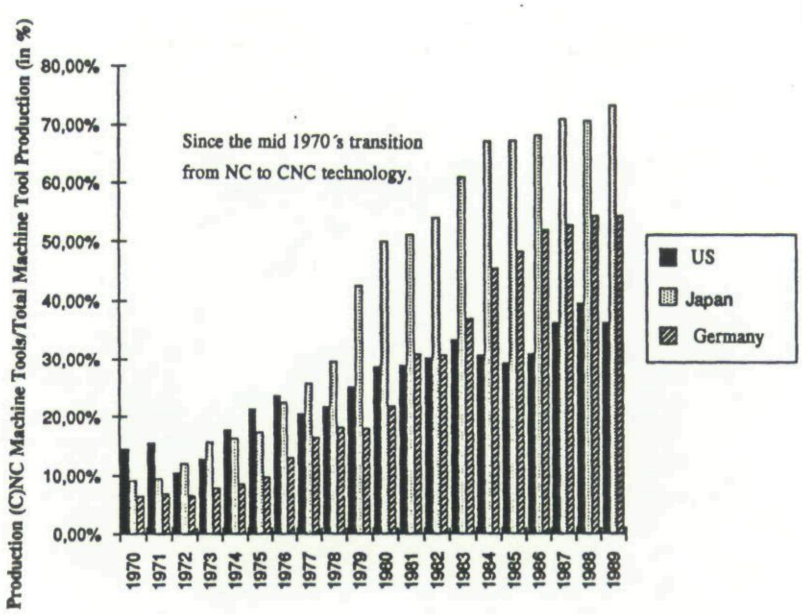
Sources: NMTBA; own calculations.

Fig. 3. Growing Japanese Import Penetration of US Machine Tool Market (in percent of annual US machine tool consumption), 1974—1989.

How has the production and trade of NC machine tools evolved in the US, Japan and Germany? The NC boom started with the advent of micro-computer technology on the late 1970's. In each of the three countries, NC machine tool production has risen faster than overall machine tool production. The most dramatic increase has occurred in Japan where the number of NC machine tools as a percent of total machine tools produced has risen from a mere 9.1% in 1970 to 73% in 1989 (see Figure 4). In the US, the growth of the share of NC machine tools in total machine tool production has been much slower. In 1989, NC machine tools accounted for only 36% of total US machine tool production. In Germany, the corresponding percentage was 39.3%. An OLS-estimation of the diffusion model of Fisher and Pry (1971) for both the US and Japan confirms that the speed of diffusion of NC technology during the 1970's and 1980's was significantly lower in the US than in Japan (Wieandt, forthcoming, chapter F).

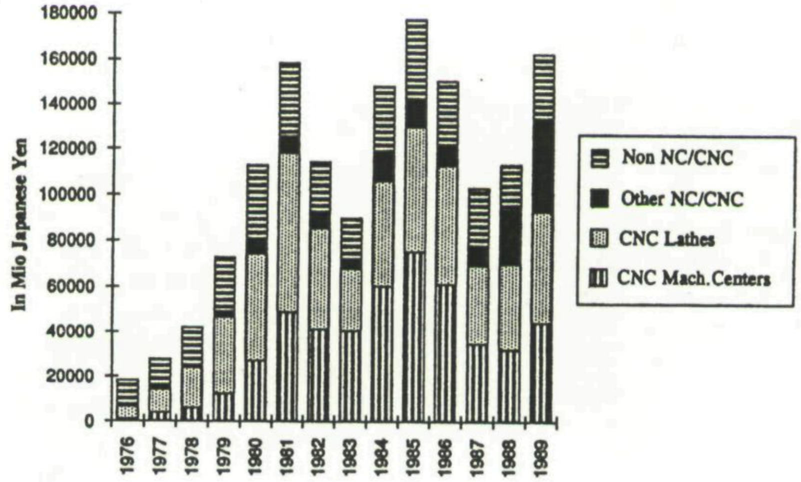
Let us look at NC machine tool trade among the three countries. Since 1970 Japanese machine tool production has risen at a compound annual growth rate of 21.3%. Most of the growth has been export driven. The US has absorbed the largest share of these exports. Germany's NC machine tool trade with Japan is also in deficit. Overall, however, Germany is still a net exporter of NC machine tools.

What are the types of machine tools with which the Japanese have created their markets? Further analysis shows that the Japanese success is due to the creation of two specific markets: NC multi-functional machining centers and NC lathes. Both types of machines are standardized general purpose machine tools. In 1989 these two types of machines accounted for almost 50% of total Japanese NC machine tool production (or over 1/3 of total machine tool production). For both machine tool categories, the US trade balance has been in deficit throughout the 1980's. Figure 5 shows to what extent Japanese exports into the US have been dominated by NC machining centers and NC lathes.



Sources: NMTBA; JMTBA: VDW; own calculations based on the value of production (machine tool + control unit) in the respective national currency.

Fig. 4. Diffusion of NC/CNC Technology in the US, Japan (metall-cutting only) and Germany, 1970—1989.



Sources: JMTBA: own calculations.

Fig. 5. Japanese Machine Tool Exports into the US (in million Japanese Yen), 1976—1989.

D. The evolution of control technology

The above analysis suggests that most of the development in the world machine tool industry can be explained in terms of the evolution of control technology. Until the early 1950's machine tool operations were either controlled manually or mechanically using cams and gears. NC technology was developed in the US in the early 1950's. With the advent of computers it evolved into computerized numerical control (CNC) and further into direct numerical control (DNC). Most of this evolution occurred outside the machine tool industry and went beyond the mechanical technology base of the typical machine tool company. Overall, numerical control technology increased the precision potential of machine tools. Complementary advances in cooling, cleaning, lubricating and sealing technologies were necessary to fully translate the precision potential opened up by numerical control into actual mechanical performance.

I. *Numerical control (NC)*

Numerical control originally denoted the use of punched tape, cards or operator push buttons to program and direct the operations of a machine tool. NC allowed the combination of flexibility and automation. By simply changing the control tape, the NC machine tool could quickly be switched to the next job, which could involve a totally different sequence of operations.

Numerical control was developed in the early 1950's in a joint effort by the John C. Parsons Corporation, the US Air Force and the Servomechanisms Laboratory at MIT (Spur, Specht and Schröder, 1990).[18] Numerical control was originally developed to solve a manufacturing problem caused by the demand of the US Air Force for a large series of uniform complex parts such as helicopter rotor blades or airplane wings. These complex parts could not be manufactured with great accuracy and uniformity by manually operated machine tools.

II. *Computerized numerical control (CNC)*

Early NC technology, however, had several drawbacks that prevented its diffusion on a large scale; "first, the logic in the control units of these first numerically controlled machine tools was made of hardwired circuitry and, if new functions were to be performed, a change in the hardware had to be made. Secondly, the components were very unreliable and, thirdly, very costly" (Jacobsson, 1956, p. 9).

The shift to computer-based and particularly microcomputer-based numerical controls (CNC) considerably increased the versatility and flexibility of machine tools, simplified programming and allowed for more functions to be controlled automatically (Jacobsson, 1986, p. 10). The central unit of these CNCs is a computer. "The philosophy underlying CNCs is to provide standardized and reliable computer hardware produced in large quantities coupled with the availability of a variety of system programs (software) which serve to provide the interface for a particular machine and production requirement" (Weck, 1984, p. 154). The incorporation of microchip technology into numerical control units was first accomplished by the Japanese firm FANUC, a former subsidiary of Fujitsu, in 1975—76. Dr. Inaba, president of FANUC, stated in 1979, that they even "applied the technical innovations in the semiconductor field to machine tools earlier than the computer industry did" (Metalworking, Engineering and Marketing, 1979, p. 42).

III. *Direct numerical control (DNC) and flexible manufacturing systems (FMS)*

Under direct numerical control (DNC) several machine tools are controlled by a single computer. The need for the operator to feed in punched cards or tapes is therefore eliminated as the machine tool is directly connected with the so called production computer. Weck (1984, p. 361) puts it as follows: "In a Direct Numerical Control system, which is designed for the direct control of several NC machines, a programmable digital computer . . . undertakes the component data processing and its transmission to the NC machine. Thus the data input into the NC machine no longer takes place on a tape reader on the NC unit but behind it. . . ."

The first DNC systems were installed in the US and Japan in the late 1960's. DNC philosophy laid the groundwork for further automation in the 1980's. Several NC machine tools and automated peripherals such as pallet systems, toolchangers, carrier and warehouse equipments etc. are now being integrated into a single cell (flexible manufacturing cells (FMC)) or even entire systems (flexible manufacturing systems (FMS)).

E. The creation, development and destruction of markets for machine tools through advances in control technology

I. *The world machine tool industry before 1977*

Before 1977, the US and Germany were the clear leaders in the world machine tool industry. The US was the largest producer and consumer of machine tools in the world and Germany emerged as the clear export leader. In the mid 1970's, German exports accounted for over 30% of world trade. The larger firms in the industry engaged in limit-pricing à la Sylos-Labini. Under their price umbrella, many small firms could find more or less profitable niches for special purpose machine tools. Most of the highly specialized niches were carved out by German machine tool builders. In this phase, innovation consisted of adapting conventional numerical control technology to individual machine tool models. Economies of scale were thus limited to individual models because each model required the design of a separate hard-wired numerical control (Pratten, 1971).[19] These model specific economies of scale were reinforced by the reduction in manufacturing cost that resulted from accumulated learning in a particular machine tool model. Economies across different models were severely limited by the sheer variety of models and the absence of modularization. In an attempt to increase returns to scale, specialized machine tool manufacturers began to extend their markets by exporting. This explains the growth in the international machine tool trade in the 1960's and 1970's.

II. *The creation, development and destruction of markets in the world machine tool industry after 1977*

In the late 1970's Japanese machine tool builders realized that the exploitation of technological opportunities created by the recent advances in computer technology allowed them to change the world-wide industry economics in their favor. Under the 'administrative guidance' (Johnson, 1982, p. 242) of the Ministry of International Trade and Industry (MITI) the Japanese machine tool industry successfully targeted the small US job shops that needed flexible, less expensive machine tools of a standardized and simple nature, with short delivery times, so that short-lived profit opportunities could be exploited.[20] The shift from NC to CNC meant that the cost of computer programs, control interface adaptations and necessary developments in related technologies such as lubrication and cooling could now be spread across different types of machine tools. The modularization of machine tool design and the cost of *creating new markets* added to the economies of scale and scope on the firm level. Japanese machine tool builders not only benefited from increasing economies of scale on the individual firm level but also on an industry-wide level. MITI designated product markets to specific firms to avoid duplication of efforts. The MITI funded Japanese Export Trade Organization (JETRO) disseminated market information, thus reducing the information cost for for the individual firm. Furthermore, MITI's coordination ensured that the learning of individual firms was spread throughout the industry. MITI also encouraged Fujitsu FANUC to become the sole supplier of controls. FANUC emphasized a high standardization, large volume strategy and provided domestic machine tool builders with simple, reliable controls. By the end of the 1970's, the market share of FANUC is estimated to have reached over 80% of the Japanese market (MIT Commission, 1989, p. 36). The existence of a dominant supplier of controls considerably reduced the interface adaptation cost for Japanese machine tool builders thus giving them an additional cost advantage. Given these large economies of scale and scope effects both on the individual firm level as well as on the industry level, it is not surprising that the largest machine tool companies in the world are now Japanese (see Table II).

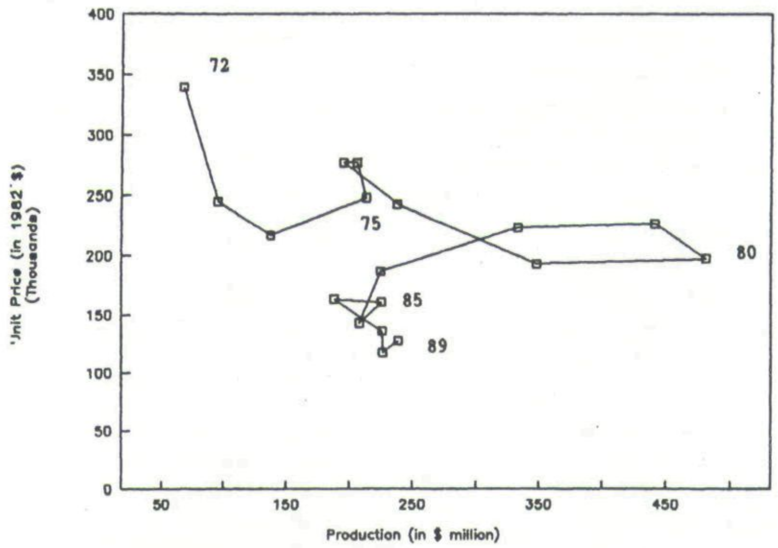
TABLE II
The major machine tool companies in the world

No.	Company	Country	Last month of year reported	Sales 1990 (in Mio. US $)
1.	Amada	Japan	9/90	1207.2
2.	Yamazaki Mazak	Japan	12/90	1150.4
3.	Fanuc	Japan	9/90	1100.7
4.	Okuma Machy Works	Japan	9/90	739
5.	Litton	US	7/90	721.8
6.	Mori Seiki	Japan	9/90	661.3
7.	Komatsu	Japan	9/90	470.7
8.	Schuler Group	Germany	12/90	464.2
9.	Toyoda Machine	Japan	9/90	464.1
10.	Gildemeister Group	Germany	12/90	443.2

Source: *American Machinist*, Blue Bulletin Newsletter 1991.

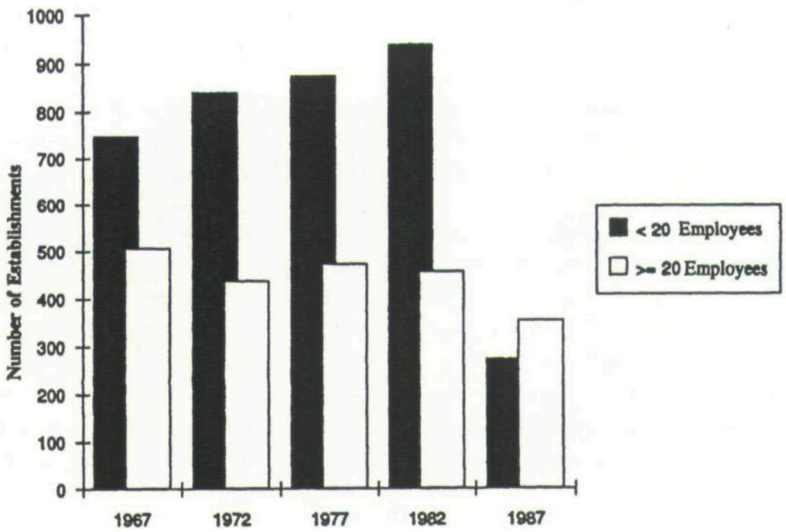
The US machine tool industry failed to exploit the shift from hardwired NC to CNC technology. Under the umbrella of the US Airforce, producers of NC machine tools were narrowly concentrating on the complex requirements of the aerospace industry. For too long, they ignored the need of the numerous small job-shops for a simpler and more reliable version of NC machine tools which would give them as advantage due to increased flexibility. When they began to wake up the Japanese competition has already *destroyed most of their domestic markets*. Despite rising demand in the late 1970's and mid 1980's, prices in the leading CNC machine tool categories were gradually forced down by limit pricing of the MITI coordinated Japanese cartel (see Figure 6 for the case of CNC lathes). The smaller US firms became less and less profitable and were forced to exit the industry in the late 1980's (see Figure 7). This pattern is consistent with Sylos-Labini's limit price theory in industries with opportunities for technological innovation as well as Phlips' more recent extension which emphasizes the reinforcing effect cooperation among incumbents can have on limiting pricing behavior.

The effect of Japanese technological competition could have been much more drastic, had a further destruction of US markets not been prevented by unilateral and bilateral trade policy measures on both sides of the Pacific. In the early 1980's the US machine tool industry accused their Japanese competitors of cartel-like behavior and pressured their government to take protectionist measures. To assuage US protectionist demands, MITI implemented a cartel in 1981 that set minimum export prices for the most successful Japanese machine tools. The cartel-like behavior of the Japanese machine tool industry was subject of the famous Houdaille petition of 1982 (Copaken, 1983; Holland, 1989, p. 171). Houdaille Corporation, a conglomerate with machine tool subsidi-



Sources: NMTBA; own calculations.

Fig. 6. Gradual Decline in Prices for (C)NC Lathes in the US, 1972—1989.



Sources: NMTBA; own calculations.

Fig. 7. Exit of US Machine tool Builders Between 1982 and 1987.

aries, claimed that the US machine tool industry had been seriously injured by Japanese 'targeting'. The ultimately unaccepted petition represents a unique attempt of an individual firm to invoke the Revenue Act of 1971 in order to ask the President to deny the investment tax credit to US taxpayers who purchase Japanese CNC machine tools. In 1986, a four year voluntary export restraint agreement (VRA) was reached that fixed Japanese imports of machining centers and CNC lathes at their 1981 levels. This VRA was extended in 1991.

German machine tool builders had been traditionally strong in the custom engineered segments of the market. Therefore, the German machine tool builders were not directly affected by the Japanese targeting of the standard machine tool segment. They managed to *develop their existing markets* by gradually adapting CNC control technology to their special purpose machine tools. However, the overall price reduction due to Japanese competition has made their specialized niches more and more unprofitable. Like their US counterparts, smaller firms were forced to exit the industry.

III. *Outlooks*

Recently, US and German machine tool builders have finally begun to react to the Japanese challenge. Several response strategies have emerged that all point in the right direction, striving for greater economies of scale and scope. Only the future can tell whether they are successful.

In the US we can observe two types of response strategies. One is exemplified by the acquisition of Cross & Trecker by Giddings & Lewis in 1991 (Pouschine, 1991). This acquisition puts Giddings & Lewis in the top ten machine tool companies in the world ranked by sales thus giving it the necessary scale to compete in the global machine tool industry. The second type of response is exemplified by Cincinnati Milacron's 'wolfpack program' (Cincinnati Milacron, 1991): In 1987, the second largest US machine tool company (after Litton Industries) decided to divest its robotics business and refocus its activities on standardized machine tools, a market segment it had completely abandoned to the overwhelming Japanese competition in the 1980's (Milbank, 1991). In a long term effort to take on the Japanese competition, Cincinnati Milacron continues to invest in product and process innovations, although the current recession adversely affects the profitability of its core business.

In Germany, two types of response strategies have emerged. One of them involves an increasing amount of modularization of machine tool parts to reap bigger economies of scale across different models (The Economist, 1991, p. 75). The other response is still being discussed right now (Manager Magazin, 1992, p. 8). It would involve the creation of a large machine tool holding that would combine the largest machine tool builders in the country to reap economies of scale scope in general administration, R&D and distribution. The ongoing recession has reinforced the pressure of Japanese price leadership on those machine tool builders which are still competing in the standardized general purpose segment. The dramatic decline in sales and profitability has recently eaten up half of the capital stock of two traditional machine tool builders in the South, Maho and Deckel, and is forcing them to standardize their product ranges and pool their production activities in order to survive in the world markets.

F. Conclusions

The world machine tool industry seems to follow the hypothesized pattern of market creation, development and destruction through innovation. Sylos-Labini's oligopoly theory and its extension of Phlips seem to give a good explanation of the effect of control technology innovation on the structure of the world machine tool industry. It is noteworthy, that the technological developments that have increased concentration in the machine tool industry seem to reduce concentration in the downstream manufacturing industries (Meredith, 1977). The impact of innovation in up-stream industries on the structure of downstream industries merits further research. With regard to industrial policy and individual firm strategy the example of the world machine tool industry illustrates that in addition to inventions and the building of technological know-how, anticipation and quick exploitation of technological opportunities through large-scale commercialization are the keys to sustained competitiveness.

Acknowledgements

I would like to than Professor Albach and two anonymous referees for their helpful comments on earlier versions of this paper. I would also like to thank the NMTBA, the JMTBA and the VDW for providing me with the necessary statistics. Special thanks to Daniel F. Keen, the international economist of the NMTBA, who repeatedly helped me gain access to numerous international machine tool statistics.

Notes

[1] NMTBA, 7901 Westpark Drive, McLean, VA 22102-4269, USA.

[2] JMTBA, Kikai Shinko Kaikan, 5—8, Shibakoen 3-chome, Minatoku, Tokyo 105, Japan.

[3] VDW, Corneliusstr. 4, W-60325 Frankfurt/Main, Germany.

[4] The ideal approach would have been to regress market shares on an input (e.g. R&D expenditures, R&D personnel etc.) or output measure (e.g. invention count, patents filed etc.) of innovation. Unfortunately, such data is not readily available and collection of primary data was beyond the scope of this study.

[5] See Sylos-Labini, 1969 (1956), and Modigliani's review article (1958).

[6] If not mentioned otherwise NC is used synonymously with CNC.

[7] The distinction between endogenous and exogenous sunk cost goes back to Sutton, 1991.

[8] For a transaction cost rationale for vertical integration see Williamson, 1985, pp. 85—102. Williamson builds on Coase, 1937.

[9] See the overview in Cohen and Levin, 1989, p. 1076.

[10] Modigliani has coined the term 'Sylos postulate' for this assumption.

[11] Sylos-Labini, 1969 (1956), p. 54. Sylos-Labini's insight goes back to Sraffa, 1926.

[12] See Modigliani, 1958, for a numerical example.

[13] Sylos-Labini (1969, p. 54) continues: "Otherwise, we would run the danger of remaining in the fantastic world of reaction curves and conjectural variations — a world where everything might and nothing need happen."

[14] See NMTBA, 1990, glossary.

[15] See also Carlsson and Jacobsson, 1990.

[16] See Payne and Sciberras, 1985, p. 83.

[17] The stronger dollar in the early 1980's can only partially explain Japanese success in the US market. Apparently, a weaker dollar neither helped US industry to ward off Japanese imports in the late 1970s nor helped it to regain ground in the second half of the 1980s.

[18] Sonny presents evidence that the principles of numerical control had already been discovered in the early 1940's by two different companies (see Sonny, 1971, p. 69).

[19] Pratten (1971) estimates the fixed cost of model design to be 10% of unit cost on average.

[20] The argument that the Japanese success is mainly due to a combination of superior marketing strategy and policy is developed by Kotler et al., New Competition, 1985, and Sarathy, Interplay, 1989. Friedman disagrees with this argument (Friedman, Miracle, 1988). He suggests that most of the success of the Japanese machine tool industry can be explained by the prevalent flexible manufacturing paradigm. The prevalence of this paradigm in turn created a unique user pull for standardized general purpose machine tools such as multi-functional machining centers.

References

Abell, Derek F., 1989, *Defining the Business, The Starting Point of Strategic Planning*, Englewood Cliffs, NJ: Prentice Hall.

Albach, Horst, 1991, *Innovation, A Cross-Cultural Perspective*, Academy of Science and Technology in Berlin, Berlin: draft-report, mimeographed.

American Machinist, 1991, *World Machine-Tool Output Survey*, February, 35—39.

Arrow, Kenneth J., 1962, 'Economic Welfare and the Allocation of Resources for Invention', in Richard R. Nelson (ed.), *The Rate and Direction of Inventive Activity*, Princeton: Princeton University Press.

Boston Consulting Group (ed.), 1990, *Europastudie für ausgewählte Zielländer für den VDW*, several volumes, Düsseldorf: mimeographed.

Carlsson, Bo, 1989, 'Small-Scale Industry at a Crossroad: U.S. Machine Tools in Global Perspective', *Small Business Economics* **1**, 245—261.

Carlsson, Bo and Staffan, Jacobsson, 1990, *What makes the Automation Industry Strategic?*, unpublished research paper, Case Western Reserve University, Cleveland: mimeographed.

Cincinnati Milacron (ed.), 1991, *Annual Report* 1990, Cincinnati, OH.

Coase, Ronald H., 1937, 'The Nature of the Firm', *Economica N.S.* **4**, 386—405.

Cohen, Wesley N. and Ronald C. Levin, 1988, 'Empirical Studies of Innovation and Market Structure', in Richard Schmalensee and Robert D. Willig (eds.), *Handbook of Industrial Organization*, vol. 2, Amsterdam: North-Holland, pp. 1059—1107.

Copaken, Richard D., 1988, 'The Houdaille Petition: A New Weapon Against Unfair Industry Targeting Practices', *The George Washington Journal of International Law and Economics* **17** (2), 211—247.

Friedman, David, 1988, *The Misunderstood Miracle, Industrial Development and Political Change in Japan*, Ithaca: Cornell University Press.

Fellner, William, 1951, 'The Influence of Market Structure on Technological Progress', *Quarterly Journal of Economics* **56**, 556—577.

Fisher, J. C. and R. H. Pry, 1971, 'A Simple Substitution Model of Technological Change, *Technological Forecasting and Social Change* **3**, 75—88.

Holland, Max, 1989, *When the [Machine] Stopped, A Cautionary Tale from Industrial America*, Boston, MA: Harvard Business Press.

Jacobsson, Staffan, 1986, *Electronics and Industrial Policy: The Case of Computer Controlled Lathes*, London: Allen & Unwin.

Jonson, Chalmers, 1982, *MITI and the Japanese Miracle: The Growth of Industrial Policy 1925—1975*, Stanford, CA: Stanford University Press.

Kamien, Morton I. and Nancy L. Schwartz, 1970, 'Market Structure, Elasticity of Demand, and Incentive to Invent', *Journal of Law and Economics* **13**, 241—252.

Kotler, Philip, Lim Fahey and Somkid Jatusripitak, 1985, *The New Competition*, Englewood Cliffs, NJ: Prentice-Hall.

Manager Magazin (ed.), 1992, 'Pläne für den Tag X', April, 8—11.

Meredith, J., 1987, 'The Strategic Advantage of New Manufacturing Technologies for Small Firms', *Strategic Management Journal* **8**, 249—258.

Metalworking, Engineering and Marketing, September 1979, p. 42.

Milbank, David, 1991, 'Grinding It Out: After a Flop in Robots, Cincinnati Milacron Is Back to Machine Tools', *The Wall Street Journal*, Friday, October 4, A1 and A4.

MIT Commission on Industrial Productivity (ed.), 1989, 'The US Machine Tool Industry and its Foreign Competitors', working paper prepared by Artemis March, Cambridge, MA.

MITI (ed.), 1990, *Current Production Statistics Survey*, Tokyo.

Modigliani, Franco, 1958, 'New Developments on the Oligopoly Front', *Journal of Political Economy* **31** (3), 215— 232.

NMTBA (ed.), 1990, *The Economic Handbook of the Machine Tool Industry, 1990—91*, McLean, VA.

O'Brien, Peter, 1987, 'Machine Tools: Growing Internationalization in a Small Firm Industry', *Multinational Business* **4**, 23—34.

Payne, B. D. and E. Sciberras, 1985, *Machine Tool Industry, Technical Change and International Competitiveness*, Harlow, Essex: Longman.

Phillips, Almarin, 1966, 'Patents, Potential Competition, and Technical Progress', *The American Economic Review* **56**, 301—310.

Phillips, Almarin, 1971, *Technology and Market Structure*, Lexington, MA: D.C. Heath.

Phlips, Louis, 1980, 'Intertemporal Price Discrimination and Sticky Prices', *The Quarterly Journal of Economics* **94**, 525—542.

Pouschine, Tatiana, 1991, 'Give It the Gas', *Forbes*, September 16.

Pratten, C. F., 1971, 'Economies of Scale for Machine Tool Production', *Journal of Industrial Economics* **19** (April), 148—165.

Sarathy, Ravi, 1989, 'The Interplay of Industrial Policy and International Strategy: Japan's Machine Tool Industry', *California Management Review* **31**, 132—160.

Scherer, Frederic, M., 1980, *Industrial Market Structure and Economic Performance*, 2nd edition, Chicago: Rand McNally.

Schumpeter, Joseph A., 1987, *Kapitalismus, Sozialismus und Demokratie*, 6th edition (1st edition 1942), translated from English by Dr. Susanne Preiswerk, Tübingen: Francke Verlag.

Sonny, J., 1971, *Technological Change in the U.S. Machine Tool Industry, 1947—1966*, dissertation, New School for Social Research, New York.

Spence, A. Michael, 1975, 'Monopoly, Quality, and Regulation', *Bell Journal of Economics* **6**, 417—429.

Spur, Günther, D. Specht and S. Schröder, 1990, *Die Numerische Steuerung — Fallstudie einer erfolgreichen Innovation aus dem Bereich des Maschinenbaus*, Arbeitsgruppe "Erfolgsbedingungen technischer Innovationen in Industrieländern" an der Akademie der Wissenschaften zu Berlin, unpublished research paper, Berlin.

Sraffa, Pietro, 1926, 'The Laws of Returns under Competitive Conditions', *The Economic Journal* **36**, 535—550.

Sutton, John, 1991, *Sunk Cost and Market Structure: Price Competition, Advertising, and the Evolution of Concentration*, Cambridge, MA: The MIT Press.

Sylos-Labini, Paolo, 1969, *Oligopoly and Technical Progress*, revised edition (first Italian edition 1956), translated from Italian by Elizabeth Henderson, Cambridge, MA: Harvard University Press.

The Economist, 1991, 'Less Is More', May 25, 75—76.

VDW, 1989, *Wichtige Zahlen des deutschen Werkzeugmaschinenbaus 1989*, Frankfurt/Main.

Weck, Martin, 1984, 'Automation and Control', *Handbook of Machine Tools*, Volume 3, translated from German into English, New York: Wiley & Sons.

Wieandt, Axel, 1993, 'Die Entstehung von Märketn durch Innovationen', *Wissenchaftszentrum Berlin*, discussion papers FSIV no. 93-12.

Wieandt, Axel, forthcoming, *Die Entstehung, Entwicklung und Zerstörung von Märkten durch Innovationen*, Stuttgart: Schäffer-Poeschel.

Williamson, Oliver E., 1985, *the Economic Institutions of Capitalism*, New York: The Free Press.