A list of Working Papers on the last pages

No. 114, 1983

The Microeconomics of Organization and Productivity Change - The Use of Machine Tools in Manufacturing

by

Bo Carlsson

Paper presented to the IUI Conference on:
The Dynamics of Decentralized (Market) Economies
Stockholm-Saltsjöbaden, Grand Hotel
August 28 - September 1, 1983

Sponsored by:
The Marcus Wallenberg Foundation for International Cooperation in Science
and organized jointly by the Industrial Institute for Economic and Social Research (**IUI**) and the Journal of Economic Behavior and Organization (**JEBO**).

December, 1983

THE MICROECONOMICS OF ORGANIZATION AND PRODUCTIVITY CHANGE - THE USE OF MACHINE TOOLS IN HISTORICAL PERSPECTIVE

by

Bo Carlsson

Paper presented to the IUI Conference on:

THE DYNAMICS OF DECENTRALIZED (MARKET) ECONOMIES
Stockholm-Saltsjöbaden, Grand Hotel
August 28 - September 1, 1983

Sponsored by:
THE MARCUS WALLENBERG FOUNDATION FOR INTERNATIONAL COOPERATION IN SCIENCE
and organized jointly by the Industrial Institute for Economic and Social Research (IUI) and the Journal of Economic Behavior and Organization (JEBO).

THE MICROECONOMICS OF ORGANIZATION AND PRODUCTIVITY CHANGE -- THE USE OF MACHINE TOOLS IN HISTORICAL PERSPECTIVE

by Bo Carlsson

Introduction

Machine tools are the nitty-gritty of manufacturing technology in all metalworking industries which make up nearly half of manufacturing industry in developed industrial countries. Machine tools are defined as power-driven machines that are used to cut, form or shape metal.

The central thesis of this paper is that machine tools have had a great deal to do with rising productivity in manufacturing industry since the Industrial Revolution. The impact has been both direct and indirect: The direct impact consists of rising labor productivity through the use of faster, more accurate, more mechanized machines, and of higher capital productivity through higher operating rates, greater reliability, and higher utilization rates. The indirect impact is the result of the organizational changes affecting both labor, capital, raw materials, and energy which the use of new or improved machine tools has either necessitated or facilitated.

The magnitude of the impact has varied over the years, largely dependent on what the areas of application have been and the extent to which new production methods have made possible the production of entirely new products or lowered the cost of existing products sufficiently to create new markets. The composition of the impact as regards direct and indirect effects on productivity also seems to have shifted over time. The main impact in recent years seems to have been indirect, i.e., through organizational changes.

There are two reasons why taking an historical approach to this subject seems appropriate, indeed almost necessary. One is that without the historical background, it is difficult to understand the revolutionary changes in the micro organization of industrial production that are currently taking place. The other reason is that at a Conference honoring the memory of Joseph A. Schumpeter it seems imperative to take such a long view, stressing the fundamental role of innovation:

> Since what we are trying to understand is economic change in historic time, there is little exaggeration in saying that the ultimate goal is simply a reasoned (=conceptually clarified) history, not of crises only, nor of cycles or waves, but of the economic process in all its aspects and bearings to which theory merely supplies some tools and schemata, and statistics merely part of the material. It is obvious that only detailed historic knowledge can definitively answer most of the questions of individual causation and mechanism and without it the study of time series must remain inconclusive, and theoretical analysis empty. It should be equally clear that contemporaneous facts or even historic facts covering the last quarter or half of a century are perfectly inadequate. For no phenomenon of an essentially historic nature can be expected to reveal itself unless it is studied over a long interval. An intensive study of the process in the last quarter of the seventeenth and in the eighteenth century is hence a most urgent task, for a quantitative and carefully dated account of a period of 250 years may be called the minimum of existence of the student of business cycles. (Schumpeter, 1939, p. 220.)

The paper is organized in the following way. Section II contains a review of the historical development of machine tool technology, paying particular attention to the role of interaction between producers and users of machine tools, the organizational changes connected with the introduction of new machine tools, and the creation of new markets resulting from some fundamental changes in production technology.

Section III of the paper focuses on the way in which recent development differs from that in earlier periods, particularly discussing the increasing importance of flexibility at the expense of scale economies in production and the shifting emphasis from development of individual pieces of machinery to integration and control of entire manufacturing processes, i.e., the increased need for a systems approach. The final section summarizes the results and draws out the implications for manufacturing technology in the future.

II. Historical Development of Machine Tools

II.1 1775-1850: Basic Machine Tools Are Developed

Machine tools have been an integral part of the industrial growth process ever since the Industrial Revolution in England in the latter part of the 18th century. While it is true that certain machine tools existed long before then, there is no doubt that the development of machine tools as we know them today is closely linked to the first several decades of the Industrial Revolution, namely from about 1775 to about 1830. Prior to that time, practically all machinery, or what little of it existed, was made of wood, and nearly all machine tools were geared to work in softer materials. (Roe, 1916, pp. 3-4.)

It was in the cotton textile industry that industrial machinery was first used to a significant extent. Through a series of inventions during the eighteenth century, the production of textiles had been entirely transformed. But even the new textile machines were largely made of wood. It was only after the puddling process for producing pig iron through the use of coke rather than charcoal was invented in 1784 (Mantoux, 1961, pp. 293-4) that iron became cheap enough to become a major industrial raw material. With the use of iron and steel came also that of metalworking machinery and therefore of machine tools as well.

There was a great deal of interdependence among the new technologies which constituted the core of the Industrial Revolution:

> In 1750 iron was used in machines and structures only where wood or another cheaper and more easily wrought material simply would not do. By 1830 iron was the first material considered by engineers and mechanicians for a wide range of uses ... This enormous difference in the employment of iron came about through a complex of interacting innovations. The supply of iron was increased when the steam engine multiplied the ironmaster's supply of power; the rapidly increasing use of steam engines in turn increased the demand for cast iron; new techniques of iron-making further increased the quantities that could be made economically; and the increased supply of iron was rendered more useful by a new class of tools, called machine tools, that could cut hard metal, both in its cast and wrought form. (Ferguson, 1967, p. 264)

Indeed, it is probable that Watt's steam engine (1775) would have been a failure, had it not been for the improved accuracy provided by Wilkinson's new boring machine. This made it possible to obtain a cylinder of sufficient roundness for the steam engine to work efficiently. (Roe, pp. 1-2.) Similar problems plagued all machinery in the early days of the Industrial Revolution. With machines now being used with much higher degrees of precision, under much heavier loads, and at speeds unheard of before, the demand for new and improved machine tools grew enormously. It is no wonder, therefore, that the first few decades of the 19th century witnessed a whole range of new machine tools and significant improvements of older designs, and that the great bulk of this development took place in England, the cradle of the Industrial Revolution, and the only country at the time capable of using machine tools to any considerable extent. Among the machine tools developed during this period are the modern lathe, the gear-cutting machine, the planer, and the shaper.

While these machine tools were developed in conjunction with the development of industrial machinery in general, and almost entirely in England, there was at the same time a different type of change taking place in America.[1] The development in the United States appears to have been much more closely associated with the needs of particular industries. It started with the idea of manufacturing arms with interchangeable parts, first in the small arms factories of Eli Whitney and Simeon North in Connecticut and later in the United States Armories in Springfield, Massachusetts, and Harper's Ferry, Virginia.

The essential ingredients of what later came to be known as the "American System" of manufacture of interchangeable parts were the following: the introduction into the making of arms of the so-called factory system (which was already in use in making textile machinery) provided a high degree of specialization and division of labor; but the specialization was carried even further than before by breaking down each task into several operations with each worker responsible for only one or two operations. The use of patterns or "jigs" for filing and drilling operations made it possible to achieve a high degree of accuracy even in manual operations; the breakdown of each task into a number of single operations made it relatively easy to mechanize each operation, thereby attaining both an even higher degree of accuracy and the possibility of extending the use of power tools. The system was further enhanced by the invention of several new machine tools, among them the milling and the grinding machine.

It is important to point out that technological change in machine tools, as in other areas, has had an element of labor saving all along. There is no doubt that one of the factors which motivated Eli Whitney to introduce his new system for making guns was the lack of skilled mechanics in the United States. (Roe, pp. 132-3.) There has been a great debate in the economic history literature about the labor-saving bias of innovation in America relative to Britain in the early 19th

[1] If the presentation here appears heavily concentrated on machine tool development in England and the United States, it merely reflects the fact by far the dominant contributions to this technology originated in England until the mid-19th century and in America from then on until the last decade or so.

century. (See e.g. Habakkuk (1967) and David (1975).) But important as the labor-saving element is, it represents only a part of the economic impact of technological change. Just as important, and in a dynamic sense even more important, is the element of introducing or facilitating entirely new products and of vastly improving the quality of existing products. This element has largely been ignored in the economic debate. (See, however, Ames & Rosenberg, 1968.) Although the system of manufacture of interchangeable parts did save labor, especially skilled labor, it also formed the embryo to a whole new philosophy of manufacturing which later became the basis for the success of American industry and for the position of technological leadership which it achieved.

II.2 1850-1900: Machine Tools Come of Age and America Takes the Lead

At mid-century, Great Britain was still leading in most fields of technology, including machine tools. The "American System" was an exception. But by 1853, it was being exported to England in the form of machinery and knowhow to produce arms using American methods at the Enfield Arsenal in Britain. (See Ames & Rosenberg.)

In the second half of the century, technological change in machine tools became gradual and universal rather than associated with spectacular changes in particular types of machine tools:

> For the majority of the major types of machine tools, change during the period 1850 to 1914 was essentially a series of minor adaptions and improvements, which over the period as a whole markedly increased the capabilities and the ease of operation of the tools, but did not change their basic forms, except through the introduction of different sizes of tools. New types were introduced, notably milling, grinding and gear-cutting machines, but with these also, once the initial invention was made, the basic design of the machine tools changed little before 1914. Increases in cutting speeds, and much greater accuracy and precision, were the result of improvements in tool steels and in driving mechanisms, and these were applied throughout the field, but their adoption was, at least in Britain, slow and steady rather than spectacular. (Floud, 1976, p. 31.)

The changes in machine tools which took place in this period were generated in response to two types of pressure: as new industries arose and modern methods of production spread to older sectors as well, new tools and modifications to old tools were required. Also, machine tool builders produced new tools and modified old ones in order to take advantage of developments in power generation and in metals technology, especially towards the end of the century. (Floud, p. 20.) Thus, there were elements of both demand pull and technology push, but the former seem to have dominated.

However, there appears to have been a major difference between the development in Britain and that in America as far as both manufacturing methods in general and machine tools in particular are concerned. In America, the industrial development was characterized by the spread of mass production methods to a much larger extent than in Britain. The "American System" of manufacture spread from the national armories first into production of clocks and then into that of entirely new devices such as sewing machines and typewriters. The 1880s witnessed the peak of railroad building in America, and mass production methods spread to locomotives and, about the same time, also into bicycles. The diffusion of mass production methods and interchangeability required both precision tooling and high-speed machines. (Pursell, 1967, pp. 399-400.)

It may be argued that it was precisely this emphasis on mass production methods, standardization, and specialization which gave America the technological lead before the end of the century.

> While British machine-tool builders had initiated the age of machine tools and dominated the market in Britain and on the Continent, American tool-builders had developed new machine tools and new methods of using them for mass manufacture. In the second half of the 19th century these important innovations were expanded and added to until the leadership in machine-tool design and manufacture was in American hands. Even French and German machine shops imported the more expensive but vastly superior American machine tools; and in some fields, such as small-arms manufacturing, British shops were using tools based upon American designs, if not actually imported from America.

> The American innovations centered around machine tools for mass manufacture largely by means of interchangeable parts. These included more automatic machine tools, more specialized machine tools, improvements in shop precision of measurement coupled with machine tools capable of greater precision. All these advances were made possible by important improvements and modifications of the classical machine-tool designs as well as by the addition of new ones -- the turret lathe, the automatic screw machine, the gear-shaper and hobber, the milling machine, and the grinding machine. (Woodbury, 1967, pp. 623-4.)

II.3 1900-1939: The Automobile Dominates Machine Tool Development

Toward the end of the century, the automobile industry took over from the bicycle manufacturers the role as the leading machine tool user. No industry has had a more profound influence on the development of machine tools in the 20th century than the automobile industry.

> During (the first half of the 20th century), the automobile industry was a particularly important factor in the evolution of machine tools and in the growth of the machine tool industry. Its most obvious role was that of customer for the machine tool industry's tools and "knowhow" reflecting production techniques used in other industries. However, the automotive industry also contributed much to the development of better and stronger materials, to more economical production methods, to the progress of standardization and the advance of machine tool design and construction. (Wagoner, 1966, p. 22.)

Thus, the automobile industry had a far-reaching impact not only on machine tools but also on industrial materials and techniques in general:

> One of the biggest problems which the automobile designer had to face was that of finding ways of building a machine which would withstand the vibration and shock to which the automobile was subjected by rough roads and comparatively high speeds. This need was met by the development of a series of alloy steels which were much stronger and tougher than earlier steels. Automobile buyers and builders also began to demand stronger, quieter running gears. This resulted in demands for improvements in the methods of gear production, and for better machines for

> grinding gears. The automobile industry was also responsible for the extention of the use of antifriction bearings of both the ball and roller types, and for rapidly extending the application of flooded or forced systems of lubrication. The latter had not been used for small machines but their advantages soon became obvious to machinery builders including machine tool builders. (Wagoner, pp. 22-3.)

Most of these advances required improvements in machine tools, e.g. better grinders for gears and ball bearings, and machines capable of handling harder and stronger materials. But the most pervasive change in machine tools and in production methods in general resulted from the introduction of a high degree of mechanization through the assembly line. In 1899, Ransom E. Olds built the first (stationary) assembly line for cars. In 1908, a special machine was developed to adz, bore and trim the ends of railroad ties. This machine is claimed to be the forerunner of the automatic transfer machine. But the truly revolutionary change was the introduction by Henry Ford of the moving assembly line in 1913. Through this innovation, Ford reduced the typical assembly time needed for his Model T from a day and half to an hour and a half. But this caused problems for the machine shops to supply components as fast as required. Thus, the need arose for machine tools of all kinds with much higher operating rates, with more automatic feed devices and substantially increased accuracy in order to avoid problems further down the production line. Responding to this need, E.P. Bullard, for example, invented a machine that reduced the time required to make a fly-wheel from eighteen to about one minute. Precision cylindrical grinders enabled the auto industry to build efficient engines; automatic machines for piston ring manufacture and a multi-spindle screw machine were invented, etc. (American Machinist, 1977, pp. E-5-16.).

The moving assembly line is another example of a new technology having an impact far beyond the large labor and time saving which it made possible. By reducing the cost of a car by over 50 % (from over $600 to less than $300), it made automobiles affordable for a vastly larger number of people - essentially creating a new market. Despite the outbreak of World War I, Ford's production rate of the Model T nearly trebled in three years and increased more than tenfold by 1925-26. (Ibid., p. E-6.)

However, in 1918, after the United States entered the war, car production was cut back in order to make room for war materials. Arms production increased dramatically, and so did machine tool shipments: from less than $40 million in 1913 to over $200 million in 1917. As machine tool firms were busy expanding production, the development of new tools and production methods slowed down.

After the war ended, automobile production resumed its growth, and assembly line operations expanded rapidly. However, there were no major changes in machine tool technology during the early 1920s. The changes that did occur were relatively minor: increased production capacity, improved methods to power machine tools, reduced vibration by making motor drives part of the general machine design, individual motorization of each function of the machine, increased standardization of machine components, improved lubrication and rigidity, etc. (American Machinist, pp. F-7-8.)

In areas besides machine tools, there were some important technological changes, however, especially in the consumer goods field. Part of the consumer goods boom of the 1920s was due to new steel-fabricating techniques, particularly continuous sheet rolling, which made it possible to produce not only automobiles but also appliances and many other products with consistently flat sheet steel. (Ibid., p. F-2.)

At the end of the 1920s there emerged two major new technologies whose economic impact, however, was delayed because of the Great Depression. One of these technologies was cemented carbide as a tool material. Alloys of carbide had originally been developed during the First World War for use in antitank projectiles. The material was adapted for use in machine tools by the Krupp Steel Works in Germany in 1928 and a few months later by Carboloy in the United States. But because of the problems inherent in adapting machine tools to the new technology and because of the intervening Depression, it was not until 1939 that machine tools had been developed in America with sufficient power and rigidity to use carbides effectively. (Ibid., p. G-8.) It is not unlikely that the Germans were ahead in this technology at the outbreak of World War II.

The other major machine tool technology of the interwar period was the transfer machine. Transfer machines consist of a number of smaller machines or work stations, each for a separate operation such as drilling or milling, organized to work together in such a fashion that a workpiece is automatically put in place at one work station, operated on there, then transferred automatically to the next work station, etc. Work is performed simultaneously at all work stations, and several operations may be performed simultaneously at each work station. A typical application of a transfer machine is a series of finishing operations on a wheel housing or an engine block. The transfer line principle had been applied as early as 1888 in watch making, and further attempts had been made in 1908 (in the production of railroad ties) and in 1920 (in producing automobile frames). A larger scale approach was made at the Morris automobile plant in Coventry, England, in 1924, where several operations were combined in a single machine rather than providing mechanical handling between separate machines. But the real breakthrough did not come until the Graham-Paige Motors Corporation installed the first true transfer machine for high-volume engine manufacturing in Detroit in 1929. Such systems then became commonplace in the automobile industry in the 1930s and spread to appliance manufacturing, electrical parts production, and many high-volume metalworking activities by the end of the decade. (Bright, 1967, pp. 643-4; and American Machinist, p G-8.)

During the Great Depression, machine tool production fell precipitously: from 50,000 units in the United States in 1929 to only 5,500 in 1932. (Wagoner, p. 363. See also Figure 1 below.) The production level remained depressed until arms production resumed on a massive scale at the end of the 1930s. Between 1939 and 1942, machine tool shipments rose from their pre-Depression peak level to over 300,000 units, a level not reached again until the late 1960s.

II.4 1939-1945: The Impact of World War II

The conversion to war production in connection with World War II had a tremendous impact on manufacturing technology. For one thing, it forced the auto industry to take over production of airplanes from the airplane manufacturers which were simply too small and poorly organized to be able to handle the enormous production volume required. In November 1938, the United States Assistant Secretary of War directed the Chief of Staff to prepare plans for an Air Force of 10,000 planes within two years. This represented over ten years' production at the then current rate of production! (Wagoner, p. 238.) The application of production knowhow from the auto industry to the manufacture of airplanes led to important cross-fertilization of the manufacturing technology between these two industries. Because of the increase in capital equipment required to accomplish this, the special production problems involved, and the high priority assigned to expansion of aircraft production, the aircraft industry became the dominating influence on technological change in machine tools during World War II, a position which it has since retained (jointly, since the late 1950s, with the space industry).

However, aircraft production was not the only industry to expand in connection with the war effort. The same story was repeated on a smaller scale in many manufacturing industries. This is reflected in machine tool production: From 1941 to 1945, the American machine tool industry produced about 800,000 machine tools, out of which about 100,000 were exported. A very large share of the whole stock of machine tools in use was renewed, largely by adding new capacity: "When the American Machinist Inventory was taken in 1940, only 28 % of the machine tools in use were less than 10 years old. Five years later, ... that figure had gone to 62 %". (American Machinist, p. G-1.) Indeed, it is no exaggeration to say that much U.S. plant capacity to this day, and even some of the machine tools in use, originated in this period.

As many industries geared up for substantially higher production and invested in new plant and equipment, the advances which had occurred in machine tool technology in the 1930s were rapidly diffused, especially cemented carbide tools and automatic transfer machines. Thus, during World War II, and in large measure directly as a result of the war effort, American manufacturing industry became equipped with new machinery for high-volume production to an extent which gave America a substantial lead over her overseas competitors in this type of technology. This, in combination with the massive destruction of industrial capacity in both Europe and Japan, probably explains a great deal of the competitiveness of American industry and the "Dollar glut" of the 1950s - but probably also the slow rate of investment and relative decline of several sections of American industry since that time.

II.5 1945-1982: "Detroit Automation" and Numerical Control

When the war ended and manufacturing industries returned to civilian production, the production methods and tools used during the war were applied to civilian products. The higher speeds and greater rigidity of machine tools required by the new tool materials also put increased demands on the motive power of machine tools: In 1938, the average horsepower of machine tools was 11.9. By 1948 it was 23.4, and by 1958 it had reached 50 horsepower, i.e., the horsepower per machine doubled every ten years. (Sonny, 1971, p. 77.)

Another important development was increased use of mechanization. As we have seen, mechanization had been an important part of technological change in machine tools since the end of the 19th century, particularly in the automobile industry, with Ford as the technological leader. Special-purpose machines had been common even before there was a machine-tool industry - built by gun makers or other specialists for their own use. Automatic control of such machines was possible since the development of the cam, i.e., a mechanical device such as a projection on a wheel which causes an eccentric rotation or a reciprocating motion to another wheel, shaft, etc. Later, methods of control using pneumatic, hydraulic, and electric devices began to develop.

During the years immediately following World War II, Ford Motor Co was in serious trouble and tried to reduce production costs by introducing mechanical handling devices between transfer machines. A new term was coined: automation. The first large-scale application of automation at Ford was the Cleveland engine plant built around 1950. It was built for machining engine blocks and had mechanical handling of the block in, out and between machines. What was new at Ford was the tying together of several separate transfer machines into a continuous system. (American Machinist, pp. G-6-8.) Even though the plant was not really automatic -- it employed more than 4,500 people, and even its most automatic element, the cylinder-block line, used 36 operators and 11 inspectors per shift -- and even though it had few feedback mechanisms and no automatic assembly of the engine, it inspired a succession of improved engine plants throughout the industry: Pontiac in 1954-55, Dodge-Plymount in 1956, and others. (Bright, pp. 651-3.)

Automation of industrial processes through mechanical devices for handling the transfer of workpieces from one machine or work station to the next, along with improved control mechanisms for both materials handling and the process itself has come to be referred to as "Detroit automation". It became the standard technology for high-volume production throughout the engineering industry in all industrial countries. But because of the large capital investment requirements, the high degree of specialization (dedication) of the machinery involved, and the virtual impossibility of making significant changes in the production line once it had been built, it could only be justified at very large scale production of standardized parts. Thus, "Detroit automation" formed the technological base for economies of scale in production throughout all metalworking industry.

But, as will be argued below, "Detroit automation", in a manner of speaking, came to represent the end of the line. True, there have been significant improvements in the speed, accuracy, and degree of mechanization of transfer machines since the mid-1950s. And in the lasst five or ten years, there have been steps taken towards making transfer machines somewhat more flexible. But for reasons which will be outlined below, the most important technological progress in the last thirty years has occurred in an entirely different direction.

Whereas the main thrust in the development of manufacturing technology in metalworking had been in the direction of improving and extending mass production methods - and this continued up through the early 1970s - there began an entirely new trend in the early 1950s which has become stronger over time and which now seems clearly dominant: the development of numerical control and the gradual shift from mechanical to electronic devices in general. For the first time, the major development of machine tools has been at low and medium scale production and has favored the manufacture of complex, non-standardized parts rather than simple, standardized parts.

> The machining operations of a numerically controlled machine are fully automatic and can be varied by just changing the information medium. Thus, the technology allows the automatic production of single pieces and small series, and introduces automation into areas which hitherto have been the exclusive realm of hand-operated machines. Mechanically controlled automatic machines have of course been economically employed for a long time - but for large-scale production only, mainly because any change in their production programme, once set, is time-consuming, cumbersome and costly. Numerical control makes this a quick and simple operation, and extends automation right down to one-off pieces. (Gebhardt & Hatzold, 1974, p. 24.)

Numerically controlled (NC) machine tools occupy an intermediate position between conventional automatic machines (transfer machines) and conventional hand-operated machines. In the beginning, the emphasis in the development of numerical control was definitely on reducing the trial and error costs associated with manufacturing complex parts with a high degree of precision on conventional, manually operated machines.

In 1948, John T. Parsons, an engineer and industrialist, saw the blueprints of a proposed Lockheed airplane to be produced for the United States Air Force. The aircraft featured a new structural concept, namely integrally stiffened wings to be achieved by hollowing out, through milling, of certain profiles in thick aluminum slabs - rather than by riveting a metal skin to a frame of individual ribs in the conventional manner. The problem was how to actually accomplish this to the exact specification required. Removing too much material, or removing it in the wrong places, would make the wing structurally unsound, resulting in wing failure and waste of resources; removing too little material would make the wing too heavy, and the plane would not fly or would be too fuel inefficient.

Parsons interested the Air Force in the idea of applying a method he had used earlier in making helicopter blades -- calculating airfoil coordinates on a crude computer and feeding these data points to a boring machine. The Air Force bought the idea. This led to a series of research projects at the Massachusetts Institute of Technology, beginning in 1949 and resulting in the adaptation of conventional machines for numerical control for use in production of military aircraft.

The fact that numerical control was developed and first applied by large companies manufacturing highly complex parts with extremely great precision requirements may partially explain why it has taken so long for numerical control to gain hold in manufacturing industry in general. Even in 1980, the share of NC machine tools in the total apparent consumption of machine tools in the developed market economies was only 25-30 %. (25 % in the EEC, 27 % in the United States, 30 % in Japan (CEC, 1983, p. 18.), and 28.5 % in Sweden (according to author's calculations based on data from Svenska Verktygsmaskintillverkares förening).) Many companies have simply failed to realize that even though NC machine tools were first applied by large firms, they were used in low-volume production. But there are undoubtedly quite a few other reasons as well.

In comparison with conventional manually operated machine tools, the advantages of numerically controlled machine tools are the following:

(1) **Savings in manpower:** in appropriate applications, numerically controlled machine tools are significantly more efficient than conventional machines. One numerically controlled drilling machine can replace approximately three conventional machines; one numerically controlled milling machine, two or three traditional machines; one processing centre may, for example, do the work of two drilling machines, one milling machine and one boring mill. Reduced manpower requirements result, of course, in lower labour costs.

(2) **Savings in machining time:** numerically controlled machines require no fixtures, curves, or stencils, so that the idle periods (in which the machine is fixed, and the workpiece clamped and measured in preparation for the actual working cycle) are greatly reduced. The more often batches of an identical workpiece are produced at different times the greater is the advantage. Further, the actual machining operation on numerically controlled machines frequently requires less time than on conventional machines. The resulting cost reductions are often substantial. In addition, the two types of time saving make it possible to use the numerically controlled machines more intensively.

(3) **Savings on tools and accessories:** the uniformity of automatic processes prolongs the life of tools and accessories; this is another source of cost reduction.

(4) **Quality improvement:** automatic positioning and control generally allow greater precision. In repeated production, deviations from the workpiece originally manufactured are impossible.

(5) **Reduction of rejects and waste:** errors and measuring faults by the operating personnel are eliminated; there are no signs of fatigue or transmission errors with automatic machines. This reduces rejects and waste practically to nil. The uniform processing and the elimination of operational errors save wear and tear as well.

(6) **Reduced stockholding:** due to the greater flexibility of production, reduced stockpiling of parts and components, as well as of finished products, becomes possible.

(7) **Other advantages** are that numerically controlled machines make the automatically controlled production of complicated pieces economically possible (previously nothing but hand-operations could be considered); they also enable firms to vary their basic models more widely or more frequently if customers want it. (Gebhardt & Hatzold, pp. 24-5.)

The first commercial applications began to appear in 1952. At the Chicago machine tool show in 1955, there were two numerically controlled lathes on display. By 1958, the first numerically controlled multi-function machine capable of automatically swapping the cutting tools in its spindle was introduced: a machining center which was in effect a combination of a milling machine, a boring machine, and a drilling machine. It could perform a series of such operations by automatically changing the tools in the spindle instead of shifting the part from one specialized machine to another. (American Machinist, pp. G-6-16.)

In the early days of numerical control and until the beginning of the 1970s, the application of the technology was heavily oriented towards production of small batches of parts, with less than 50 units in each batch. (Gebhardt & Hatzold, pp. 49-50.) But in the 1970s, increasing emphasis has been put on (1) making NC machines larger, faster, and more accurate, thus increasing their production capacity and making them more competitive with transfer machines in certain applications, and (2) integrating NC machines into larger systems. NC machines are to an increasing extent equipped with tool changing and materials handling devices which makes it possible to connect several NC machines together into larger cells or systems. In addition, the numerical controllers themselves have become more sophisticated. Whereas the early NC machines had paper tape and later integrated circuit controls, the development in the 1970s has involved computerized numerical control (CNC) -- essentially a microcomputer which stores programs for the machine and which orders and controls the operation of the machine -- and direct numerical control (DNC) which ties together several CNC machines via a central minicomputer. (DEK, 1981, pp. 132-4.) A computerized system which comprises several CNC machines, a materials handling system (perhaps in the form of industrial robots), a tool changing system, and a central control system may be referred to as a flexible manufacturing system (FMS). It serves the same purpose as a conventional automated production system (transfer machine), except that the FMS can be more easily re-programmed and can accommodate larger variations in the size and shape of workpieces and in the sequence and number of operations to be performed. Also, the fact that the system is computerized opens up the possibility of connecting it to other computerized systems within the firm. For example, to the extent that product design within the firm is computerized (via computer aided design, CAD, systems), it is possible in principle to make drawings available directly to the computer aided manufacturing system (CAM). When systems of this sort are fully implemented -- there are only a handful of such systems operational in the world today -- the degree of flexibility is increased enormously in relation to the situation only a decade ago.

II.6 Summary of the History of Machine Tool Development: Some Reflections

Thus, the nature of technological change has varied over the years. In the early days of the Industrial Revolution, up until the middle of the nineteenth century, machine tool development was closely linked with the invention and diffusion of industrial machinery in general. It was only after the middle of the century that companies began to specialize in making machine tools; up to that time, the manufacture of machine tools had been carried out more or less ad hoc by the users. (Rosenberg, 1963, pp. 417-422.) Thus, from the very beginning, the development of machine tools has been heavily influenced by users; the interaction between machine tool producers and users has been of fundamental importance all along.

By mid-19th century, most of the machine tools in use today had been developed in their basic form. Since that time, technological change in machine tools has been largely incremental. However, the sum of these incremental changes has been very large indeed, as a comparison of any machine tool today with its 100-year-old ancestor will reveal.

In America, machine tool development was from the very beginning linked with the "American System" of manufacture of interchangeable parts, specialization, standardization, and eventually mechanization and mass production. In the latter half of the nineteenth century, the spread of mass production methods into new industries gave America the technological lead over the previously dominating Great Britain.

Until the beginning of the 20th century, machine tool development was largely separate for each type of machine tool and geared to the needs of the users of that particular machine tool. (There are some exceptions to this however: e.g. the introduction of individual motor drives for each machine tool as opposed to the use of overhead shafts and pulleys, as well as improved tool materials which spread universally to all machine tools.) Machine tools became larger, heavier, more robust, more accurate, etc., in response to the needs of the particular users in each case. Some machine tools were designed for very high production rates, and there were many examples of mechanization of feeds of individual machines.

But around the turn of the century, the emergence of the automobile industry gave rise to challenges of an entirely new order of magnitude. The automobile is a very complex product even today, and it certainly was complex then in comparison with earlier industrial goods. At the same time, it was a consumer product which faced a potential mass market. Indeed, it was precisely through the introduction of better production methods and machine tools that the automobile became a mass-produced good. It was Henry Ford's relentless efforts to reduce costs which created demands for machines which were vastly more productive and at the same time more accurate than existing machines. Because of the complexity of the product, the machine tools required for its manufacture were of many different kinds. Therefore, the pressure for higher operating rates, closer tolerances, and higher degrees of mechanization spread to virtually all types of machine tools at the same time. And because of the size of the market, the impact was enormous on both manufacturing technology in general and the economy as a whole. The methods and machine tools which were adopted in the automobile industry then spread gradually to other sectors.

However, the impact of the automobile industry as far as production technology is concerned was not limited to significant improvements in individual machine tools. It also had important consequences for the organization of industrial production; the assembly line required not only better and more productive machine tools but also better ways of controlling them and of coordinating a complex set of activities at a much higher pace than before. Production began to be thought of as a system rather than as a sequence of processes carried out on separate, stand-alone machines.

By virtue of the success of the "American System" of manufactures with its emphasis on specialization, standardization, and mass production, and through the emergence of America as the technological leader (partly as a result of this very success), the ideas of mechanization and mass production have become closely intertwined. The development of production technology in the automobile industry certainly did nothing to cast doubt upon the notion of mass production as a requirement for a high degree of automation. The separation between automation and mass production remained for a new technology to achieve: numerical control.

The essence of numerical control is that it makes it possible to produce highly complex parts with a high degree of accuracy, and that an NC machine is relatively easy to program. Its programmability makes it particularly suitable for short production runs; it is ideal for manufacture of a variety of parts, each of which is produced in small batches. For large volume production (say, several hundred thousand units of a single item), it is usually cheaper to use specially designed (but inflexible) machines or series of machines (transfer lines). For single items or for very small production lots it is still cheaper to use conventional machine tools in combination with skilled labor. However, with computer-aided design and computer-aided manufacturing devices, the possibility of converting information directly from drawings into machine instructions may make it cheaper, especially in cases of highly complex parts, to use NC rather than conventional machine tools. An important reason for the economic significance, both potential and actual, of numerically controlled machine tools, is that perhaps two-thirds of the products made in the engineering industries are manufactured in batches of a size suitable for NC machine tools.

Numerically controlled machine tools provide another example of a new technology which not only reduces cost but also creates an entirely new market. It is doubtful whether the complex machining of integrally stiffened wings would have been economically feasible at all without numerical control. And without that, what would have happened to the development of jet aircraft? Also, it is doubtful whether the achievements in space in the last couple of decades would have been nearly as impressive if it had not been for the extremely high degree of precision of milling, turning, drilling, etc., which numerical control has permitted.

Beyond this, the advantages of numerically controlled machine tools are largely of an organizational nature. The metal-cutting operations which they perform are not essentially different from those performed in other machines. But the possibility of much closer interaction between design and production which they offer, the capability of making rapid and frequent design changes, the ability to accept workpieces of widely varying size and shape (whereas a transfer line is extremely limited in this regard) gives them a flexibility not available with earlier existing machinery. "The day of black automobiles and white refrigerators is long over. The name of the game today is product diversification and fast response to the changing needs of the marketplace. Mass production, as we have known it, is not compatible with these demands." (American Machinist, p. I-1.)

III Present Development Trends

III.1 Flexibility vs. Economies of Scale

The foregoing historical analysis raises the following important question: Are scale economies becoming less significant and the cost consequences of flexibility more important (economies of scale vs. economies of scope)?

Let us start with the question of why scale economies may become less important. If one wants to produce, say, 200,000 or more units a year of a particular item, there is probably no better way to do it than to use a specially built (dedicated) production line - a transfer line.

But suppose that for some reason it is desirable to change the design of the product being made -- change the dimensions somewhat, drill a different size hole, etc. If the changes are large enough, it would be necessary either to buy a new transfer line or to re-build the old one. Only very minor changes could be handled by changing heads or tools on the old machine. Even so, it would involve shutting down the machine for a very considerable period of time and carrying out the change manually.

Alternatively, suppose that the projected production volume of 200,000 units per year turns out to be too optimistic. If so, the transfer line may end up running much less time each year than planned. But because it is a highly dedicated machine, it cannot be used for anything else. In this case, the capital cost becomes considerably higher and the profits smaller than expected.

In contrast to this case of large-volume production of a single standardized part, consider a situation in which one wants to produce a family of parts, i.e. a set of parts with similar characteristics but differing slightly in size or shape. Let's say the desired production consists of 5,000 units of part A, 20,000 units of part B, 50,000 units of part C, and only 1,000 units of part D. No one of these parts is to be produced in sufficient numbers to warrant a dedicated machine. Instead, a set of machines which can be easily programmed to handle any one of these parts and then switch quickly to the next part would be more appropriate. This would be a typical application of numerically controlled machines. If desired, they could be linked together via some materials handling system, or they could be operated in batch mode. In the latter case, each batch might be accompanied by a punched tape or other device to be inserted into the numerical control unit of each machine and instructing the machine as to what operations to perform.

Each machine could perhaps perform only one operation at a time rather than several as on a transfer machine, so that it would take more machine time to get the finished part than on a transfer line.

But using a system of this sort, based on numerical control, gives a much higher degree of flexibility than a transfer machine. If it becomes necessary to change the design of one or all the parts, this can be done essentially by giving new instructions to the appropriate machines. If the allocation of production among parts A - D should turn out to be different from that originally planned, that can be easily handled. And should the total production volume fall short of the projected level, the machines could be used to manufacture other parts, if so desired.

Obviously, there is some output volume beyond which it would always pay to get a dedicated machine, and there is some output volume below which it would always be cheaper to buy NC or even conventional machines. There are and will remain to be grey areas in between in which these three types of technologies will compete. As indicated earlier, transfer machine manufacturers have begun in recent years to respond to the need for increased flexibility, e.g. by developing devices facilitating tool or head changes, thus making it possible to manufacture families of slightly varied parts on a single machine. At the same time, NC machines are becoming more productive through greater cutting speed, the addition of more spindles, better feeding and unloading devices, etc.

Now, to get back to the question of why scale economies may be becoming less important, it is clear that this is very much linked to the notion of flexibility in the manufacturing process. Essentially, the greater the need for flexibility, the more difficult it is to fully utilize a highly dedicated machine designed for a large production volume. However, the production volume is essentially determined by the type of product and the market, not by the manufacturer alone. A manufacturer who decides deliberately to produce a smaller volume than his competitors in order to use more flexible machinery may find himself doing better in slumps and worse in booms than his competitors. Who will be the most competitive in the long run is determined largely by the market growth rate and its stability. American firms, operating in a huge domestic market, have often been forced into larger scale, less flexible production than their foreign competitors. This gives them an advantage when the market is steady and growing but also a disadvantage when it is unstable or declining. But the tendencies towards convergence of large and small scale production technology which we now observe indicate that the choice of technology in the future may become substantially less dependent on scale than has been the case up to now. In addition, the internationalization of markets means that scale becomes a company characteristic, not a national one. It seems as though these are important factors in trying to understand the changes in international competitiveness which have occurred in recent years.

III.2 Reasons for the Need for Greater Flexibility

However, at the same time as the tradeoff between scale and flexibility is changing, there seems to be a secularly increasing need for flexibility in the manufacturing process. There are several reasons for this:

1. The character of competition has changed dramatically, particularly in the last decade. The internationalization of markets means not only greater competition (although the number of competitors in a particular field may actually be reduced as a result of new competitors forcing older firms out of business) but also competition of a different kind. This has been shown, for example, to be true in the machine tool industry. (See Carlsson, 1983.) But this is likely to be true not only for machine tools but also for a very large group of manufactured goods. American firms are faced with foreign competition to an extent never heard of before, while in Europe intra-European competition has been supplemented with extra-European competitors, particularly from Japan and other countries in the Far East. Thus, in both America and Western Europe there is a new element: competitors with fundamentally different cost structures and ways of doing business. This has led, among other things, to a greater variety of products being offered in the market. Given a greater choice, customers are forced to become more discriminating in their purchases. The greater their technical competence, the more features they demand on the products they buy. But unless the manufacturer is able to simply add more features as standard equipment on every product or lunless the greater variety of products leads to a substantial market expansion, this means a larger number of short production runs to produce families of parts rather than a very large production of a single part. In other words, a greater variety of features means a greater need for flexibility of the production equipment.

2. Greater competition tends to reduce the product life cycles. Hence, in order to extend the life of existing basic designs,

manufacturers are forced to make frequent small design changes. This requires capability (= flexibility) in terms of both organization and machinery.

3. The greater competitive pressure has reduced profitability and has forced companies to reduce the amount of capital tied up in their operation, i.e. to increase the capital turnover rate. Since in the engineering industry typically 50-60 percent of the operating capital is tied up in raw materials, goods in process, and inventory of finished goods (the remaining 40-50 percent being divided between plant and equipment and accounts receivable), reduced inventories has become an important target in many firms. But since the optimal inventory is determined by the time and cost required to reproduce the inventory, the more flexible the production equipment, the smaller the required inventory of finished goods. For similar reasons customers, too, want to hold down their inventories. This means reduced lot sizes and increased order frequency, which for the manufacturer means greater need for flexibility of the production equipment and of the whole manufacturing operation. The extremely high interest rates in recent years have made it even more imperative to reduce the capital tied up in the manufacturing process.

Conclusions

The analysis carried out in this paper suggests the importance of machine tools in explaining the productivity gains in manufacturing industry. It has also suggested that the organization surrounding the hardware (the machine tools) is at least as important as the hardware itself. In fact, the analysis here indicates that the organizational factors have gained in relative importance over time. This seems to square well with the fact that "total factor productivity" as conventionally measured has contributed an increasing share of total growth in manufacturing, at least in Sweden: Its contribution grew from about 1/3 in 1950-55 to over 90 % after 1965. (Carlsson, 1981, p. 338.)

The growth-generating effects of changes in organization of manufacturing activity as a resultof technological change in machine tools have been of two kinds. One is the direct impact on productivity, which hardly needs elaboration. The other growth-generatting effect is far more difficult to identify and is therefore often ignored by economists, namely the creation of new or vastly impoved products and therefore the creation of new markets. Four examples illustrate this point.

The first example is the so-called American System of Manufactures, which essentially used previously existing machine tools but organized the workers and the operating procedures around them in an entirely new way. The important new ideas here were interchangeability of parts through standaradization and a high degree of precision, increased specialization of labor, and a relatively high degree of mechanization. The principles of mass production of standardized products were gradually extended to a large variety of products, making possible their supply at prices far below those in Europe. For example, American machine tools, themselves manufactured with interchangeable parts, cost only half as much as equivalent British machine tools in the 1880s, even though the wages of the semiskilled workers employed in manufacturing them were considerably higher in the United States than in Britain. (Strassmann, 1959, pp. 117-8.)

The second example is the moving assembly line, which was essentialy a new way of organizing the logistics of automobile final assembly. The resulting improvement in productivity was so large that it generated (induced) demand for vastly improved machinery and production techniques for the supply of parts, and from there the new methods and improved machine tools spread to other sectors as well. But even in the auto itself the cost reduction was of an order of magnitude sufficient to create an entirely new mass market for automobiles.

Another example is "Detroit Automation" in the early 1950s -- the linking together, through mechanical devices, of several transfer machines for high-volume production of parts. In the 1950s and 1960s, this became the standard way to reduce costs in all high-volume manufacturing operations. not just automobiles. The resulting price reduction was as essential ingredient in creating mass markets for all kinds of household appliances.

The fourth example is numerical control, also originating in the early 1950s but having significant impact only now and in the future. In this case, the "autonomous" change was a non-mechanical way of positioning workpieces and determining the sequence and character of operations to be performed. Numerical control has opened up the possibility of extending industrial production methods and mechanization to areas previously characterized more by handicraft methods. The true potential of this technology can only be utilized when it is fully computerized, something which has not yet taken place. But even before this has happened, the economics of industrial production has been revolutionized by the cost reduction of small scale production relative to large scale and the degree of flexibility offered by the technology. Given the fact that most manufactured goods are produced in small batches, the potential impact on manufacturing costs is very large indeed -- both directly through higher productivity and indirectly through creation of entirely new markets.

Another implication of the results of this study is that the relationship between capital investment and productivity change is far less clear than commonly assumed. A lot of investment in recent years has been related to organizational changes and has had relatively small hardware components: industral robots, materials handling systems, production control systems, computers, and the like. Investments of this sort tend to increase production capacity by improving the efficiency of utilization of already existing resources, both capital and labor. But they also tend to absorb more management and engineering resources than "pure hardware" investments. This is one reason why much of the current debate, focused as it is almost entirely on material or "hardware" investment, may be far too pessimistic. Another reason is that the development of immaterial investment, particularly in the form of R&D and the build-up of foreign production and sales organizations in new geographical markets, may be such that it more than outweighs the decline in material investment. At least this is true in the case of Sweden. (See Carlsson _et al._, 1981.)

REFERENCES

American Machinist, 1977, "Metalworking Yesterday and Tomorrow", American Machinist, Vol. 121, No. 11, November 1977 (100th anniversary issue).

Ames, Edward & Rosenberg, Nathan, 1968, "The Enfield Arsenal in Theory and History", Economic Journal, LXXXVIII (1968), pp. 827-42.

Bright, James R., 1967, "The Development of Automation" in M. Kranzberg and C.W. Pursell, Jr. (eds.), Technology in Western Civilization, Vol. II. Oxford University Press, London.

Carlsson, B., 1981, "The Content of Productivity Growth in Swedish Manufacturing", Research Policy, Vol. 10, No. 4, 1981.

\- , 1983, "The Machine Tool Industry - Problems and Prospects in an International Perspective", IUI Working Paper No. 96, IUI, Stockholm.

Carlsson, B. et al., 1979, "Teknik och industristruktur - 70-talets ekonomiska kris i historisk belysning." IUI-IVA, Stockholm.

Commission of the European Communities (CEC), 1983, "The European Machine Tool Industry. Commission Statement. Situation and Prospects." SEC (83) 151 final. Brussels, February 1983.

Data- och elektronikkommittén (DEK), 1981, Datateknik i verkstadsindustrin. Datorstödd konstruktions- och tillverkningsteknik. SOU 1981:10, Stockholm.

David, Paul. A, 1975, Technical Choice, Innovation and Economic Growth. Essays on American and British Experience in the Nineteenth Century. Cambridge University Press, Cambridge.

Ferguson, Eugene S., 1967, "Metallurgical and Machine-Tool Developments" in M. Kranzberg and C.W. Pursell, Jr. (eds.), Technology in Western Civilization, Vol. I, Oxford University Press, New York, 1967.

Floud, R., 1976, The British Machine Tool Industry 1850-1914, (CUP, London.)

Gebhardt, A. and Hatzold, O., 1974, "Numerically Controlled Machine Tools," Ch. 3 in Nabseth, L. and Ray, G.F. (eds.), The Diffusion of New Industrial Processes: An International Study. Cambridge University Press, London, 1974.

Habakkuk, H.J., 1967, American and British Technology in the Nineteenth Century. The Search for Labour-Saving Intentions. Cambridge University Press, Cambridge.

Mantoux, Paul, 1961, The Industrial Revolution in the Eighteenth Century. An Outline of the Beginnings of the Modern Factory System in England, revised edition. Harper & Row Publishers, New York.

Pursell, Jr., Carroll W., 1967, "Machines and Machine Tools, 1830-1880" in M. Kranzberg and C.W. Pursell, Jr. (eds.), Technology in Western Civilization, Vol. I, Oxford University Press, London.

Roe, J.W., 1916, English and American Tool Builders, Yale University Press, New Haven.

Rosenberg, Nathan, 1963, "Technological Change in the Machine Tool Industry 1840-1910", Journal of Economic History.

Schumpeter, Joseph A., 1939, Business Cycles. A Theoretical, Historical and Statistical Analysis of the Capitalist Process, 1st ed. McGraw-Hill Book Company, Inc., New York.

Sonny, Jacob, 1971, "Technological Change in the U.S. Machine Tool Industry 1947-1966", unpubl. Ph.D. dissertation, New School for Social Research, June 1971.

Strassman, , 1959, Risk and Technological Innovation.

Wagoner, Harless D., 1966, The U.S. Machine Tool Industry from 1900 to 1950. The M.I.T. Press, Cambridge, MA.

Woodbury, Robert S., 1967, "Machines and Tools" in M. Kranzberg and C.W. Pursell, Jr. (eds.) Technology in Western Civilization, Oxford University Press, London.

WORKING PAPERS (Missing numbers indicate publication elsewhere)

1976

1. Corporate and Personal Taxation and the Growing Firm
by Ulf Jakobsson

8. Estimation and Analysis with a WDI Production Function
by Göran Eriksson, Ulf Jakobsson and Leif Jansson

1977

15. Pay Differentials between Government and Private Sector Employees in Sweden
by Siv Gustafsson

1980

25. On Unexplained Price Differences
by Bo Axell

34. Imperfect Information Equilibrium, Existence, Configuration and Stability
by Bo Axell

1981

36. Energi, stabilitet och tillväxt i svensk ekonomi (Energy, Stability and Growth in the Swedish Economy)
by Bengt-Christer Ysander

38. Utiliy in Local Government Budgeting
by Bengt-Christer Ysander

40. Wage Earners Funds and Rational Expectations
by Bo Axell

42. The Structure of the ISAC Model
by Leif Jansson, Tomas Nordström and Bengt-Christer Ysander

43. An Econometric Model of Local Government and Budgeting
by Bengt-Christer Ysander

44. Local Authorities, Economic Stability and the Efficiency of Fiscal Policy
by Tomas Nordström and Bengt-Christer Ysander

45. Growth, Exit and Entry of Firms
by Göran Eriksson

52. Swedish Export Performance 1963-1979. A Constant Market Shares Analysis
by Eva Christina Horwitz

56. Central Control of the Local Government Sector in Sweden
by Richard Murray

59. Longitudinal Lessons from the Panel Study of Income Dynamics
by Greg J. Duncan and James N. Morgan

1982

61. Var står den nationalekonomiska centralteorin idag?
av Bo Axell

63. General Search Market Equilibrium
by James W. Albrecht and Bo Axell
General Equilibrium without an Auctioneer
by James W. Albrecht, Bo Axell and Harald Lang

64. The Structure and Working of the ISAC Model
by Leif Jansson, Thomas Nordström and Bengt-Christer Ysander

65. Comparative Advantage and Development Policy Twenty Years Later
by Anne O. Krueger

67. Computable Multi-Country Models of Production and Trade
by James M. Henderson

69. Relative Competitiveness of Foreign Subsidiary Operations of a Multinational Company 1962-77
by Anders Grufman

71. Technology, Pricing and Investment in Telecommunications
by Tomas Pousette

72. The Micro Initialization of MOSES
by James W Albrecht and Thomas Lindberg

75. The MOSES Manual
by Fredrik Bergholm

76. Differential Patterns of Unemployment in Sweden
by Linda Leighton and Siv Gustafsson

77. Household Market and a Nonmarket Activities (HUS) - A Pilot Study
by Anders Klevmarken

1983

79. Energy Prices, Industrial Structure and Choice of Technology; An International Comparison with Special Emphasis on the Cement Industry
by Bo Carlsson

81. ELIAS - A Model of Multisectoral Economic Growth in a Small Open Economy
by Lars Bergman

84. Monopoly and Allocative Efficiency with Stochastic Demand
by Tomas Pousette

86. The Micro (Firm) Foundations of Industrial Policy
by Gunnar Eliasson

87. Excessive Government Spending in the U.S.: Facts and Theories
by Edward M. Gramlich

88. Control of Local Authority Expenditure - The Use of Cash Limits
by Noel Hepworth

89. Fiscal Containment and Local Government Finance in the U.K.
by Peter Jackson

90. Fiscal Limitations: An Assessment of the U.S. Experience
by Wallace E. Oates

91. Pricing and Privatization of Public Services
by George E. Peterson

94. Job Mobility and Wage Growth: A Study of Selection Rules and Rewards
by Bertil Holmlund

96. The Machine Tool Industry - Problems and Prospects in an International Perspective
by Bo Carlsson

97. The Development and Use of Machine Tools in Historical Perspective
by Bo Carlsson

99. An Equilibrium Model of Search Unemployment
by James W. Albrecht and Bo Axell

100. Quit Behavior under Imperfect Information: Searching, Moving, Learning
by Bertil Holmlund and Harald Lang

102. Collecting Data for Micro Analysis.
Experiences from the Hus-Pilot Study
by N. Anders Klevmarken

103. The Swedish Micro-to-Macro Model
- Idea, Design and Application
by Gunnar Eliasson

105. Estimation of Wage Gains and Welfare Gains from Self-Selection Models
by Anders Björklund and Robert Moffitt

106. Public Policy Evaluation in Sweden
by Bengt-Christer Ysander

108. Entry, Industry Growth and the Microdynamics of Industry Supply
by John C. Hause and Gunnar Du Rietz

109. Capitalist Organization and Nationalistic Response; Social Dynamics in Age of Schumpeter
by William Parker

110. A Nonwalrasian Model of the Business Cycle
by J.-P. Benassy

111. Disequilibrium Economic Dynamics -
A Post-Schumpeterian Contribution
by Richard Day

112. Schumpeterian Competition in Alternative Technological Regimes
by Sidney Winter

113. The Industrial Finance Systems; Europe, U.S. and Japan
by Tad Rybczynski

114. The Microeconomics of Organization and Productivity Change - The Use of Machine Tools in Manufacturing
by Bo Carlsson

115. On the Behavioral and Rational Foundations of Economic Theory
by Herbert Simon

116. Schumpeterian Dynamics
by Erik Dahmén

117. Micro Heterogeneity of Firms and the Stability of Industrial Growth
by Gunnar Eliasson

118. The Initialization Process - The Moses Manual, Part 2
by Fredrik Bergholm