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The Development and Use of Machine Tools in Historical Perspective

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by

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ABSTRACT

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Improvements and diffusion of machine tools have had a major impact on 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 direct impact arises as the use of new or improved machine tools has necessitated or facilitated organizational changes affecting both labor, capital, raw materials, and energy. The magnitude of these impacts has varied over the years with the areas of applications as new production methods have made possible entirely new products or lowered the cost of existing products sufficiently to create new markets.

The first part of the paper contains a review of the historical development of machine tool technology since the Industrial Revolution, paying particular attention to the role of interaction between producers and users of machine tools. The second part focuses on the way in which recent development differs from that in earlier periods. In particular, it is found that the major changes in machine tool technology, from the so-called American System of Manufactures in the early 19th century to the development of "Detroit Automation" in the 1950s, have tended to improve mass production methods. By contrast, the development of numerical control, beginning in 1948, has opened up the possibility of extending industrial production methods and automation to areas previously characterized more by handicraft methods. Even though this technology is not yet fully utilized, it is clear that 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.

The third section of the paper deals with the present development trends, particularly discussing the increasing importance of flexibility and the shifting emphasis from development of individual pieces of machinery to integration and control of entire manufacturing processes, i.a. through the use of industrial robots. The reasons for the need for greater flexibility in manufacturing are also identified.

THE DEVELOPMENT AND USE OF MACHINE TOOLS IN HISTORICAL PERSPECTIVE

by Bo Carlsson

Machine tools are defined as power-driven machines that are used to cut, form or shape metal. The product of the metalworking industries employing such tools make up nearly half of manufacturing output in developed industrial countries.

Clearly improvements and diffusion of machine tools have had a strong impact on 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 has arisen as the use of new or improved machine tools has necessitated or facilitated organizational changes affecting both labor, capital, raw materials and energy.

Over the years, the magnitude of these impacts has varied with the areas of application as new production methods have made possible 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 change.

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.)

Part I of the paper 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. Part II 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.

I. Historical Development of Machine Tools

I.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 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 of 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.

I.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.

But there was one very important element of technology push which occurred in this period but gained economic significance only a couple of decades later. Even at the end of the 19th century, machine shops were still a maze of lineshafts, pulleys and belts -- all having to do with the use of a central source of power (usually a steam engine) and the lack of individually powered machines. As a result, machine tools were ungainly and hazardous with exposed gears and uncontrolled drives. But in 1892, the electric motor began to be used as a drive for individual machine tools. (American Machinist, p.D-3.) In 1895, for example, the Baldwin locomotive plant in Philadelphia converted some of their lathes to individual drive so that the overhead lineshafts could be taken down (Ibid.). It is unlikely that the developments in the direction of larger and more powerful machine tools and the efficient use of improved high-speed tool steels which took place a little later would have been as important as in fact they turned out to be, had it not been for the use of individual electric motors. Electrification became widespread throughout manufacturing industry in the United States at the turn of the century, exerting a major influence on production techniques and the organization of work at all levels of industry.

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.)

I.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.

I.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.

I.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-Plymouth 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 blue-prints of a proposed Lockheed airplane to be produced for the United States Air Force. (American Machinist, p. G-6.) 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