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, often through the use of industrial robots. 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. These materials or tool handling devices may consist of mechanical devices, automatically guided vehicles, and industrial robots, or a combinaton of these. The versatility and programmability of robots make them an important, often essential, element of flexibility in integrated production 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.

## I.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 of automation from 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 cheaper even today 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. The use of industrial robots rather than mechanical devices to link various machines to each other further enhances the flexibility of NC 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.)

## II. Present Development Trends

### II.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.

## II.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 unless 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.

## III 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 result of technological change in machine tools have been of two kinds. One is the direct impact on productivity, which hardly needs elaboration. The other growth-generating 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 standardization 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 essentially 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 industry 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 an 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. Systems where all the essential pieces of equipment are electronic and where all the flows of information, parts, and tools are controlled via software are inherently much more flexible than systems based on hardware with mostly mechanical controls and linkages and where only some of the pieces of equipment are electronically guided. 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: industrial 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 and may miss the point entirely. It is perfectly possible, perhaps even likely -- although the lack of statistical information makes it impossible to prove -- that a lot more has been happening in manufacturing industry in developed industrial countries in terms of adoption of new technologies and adjustment to changing structure of demand than currently available investment figures suggest.

Another issue raised by this study is whether the current micro-electronic revolution will have market and job creating effects similar to those of the older technologies examined here, in addition to, and because of, the productivity increasing effects which have thus far completely dominated the public debate.

**NOTES**

[1] If the presentation here appears heavily concentrated on machine tool development in England and the Unites States, it merely reflects the fact that 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.

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