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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

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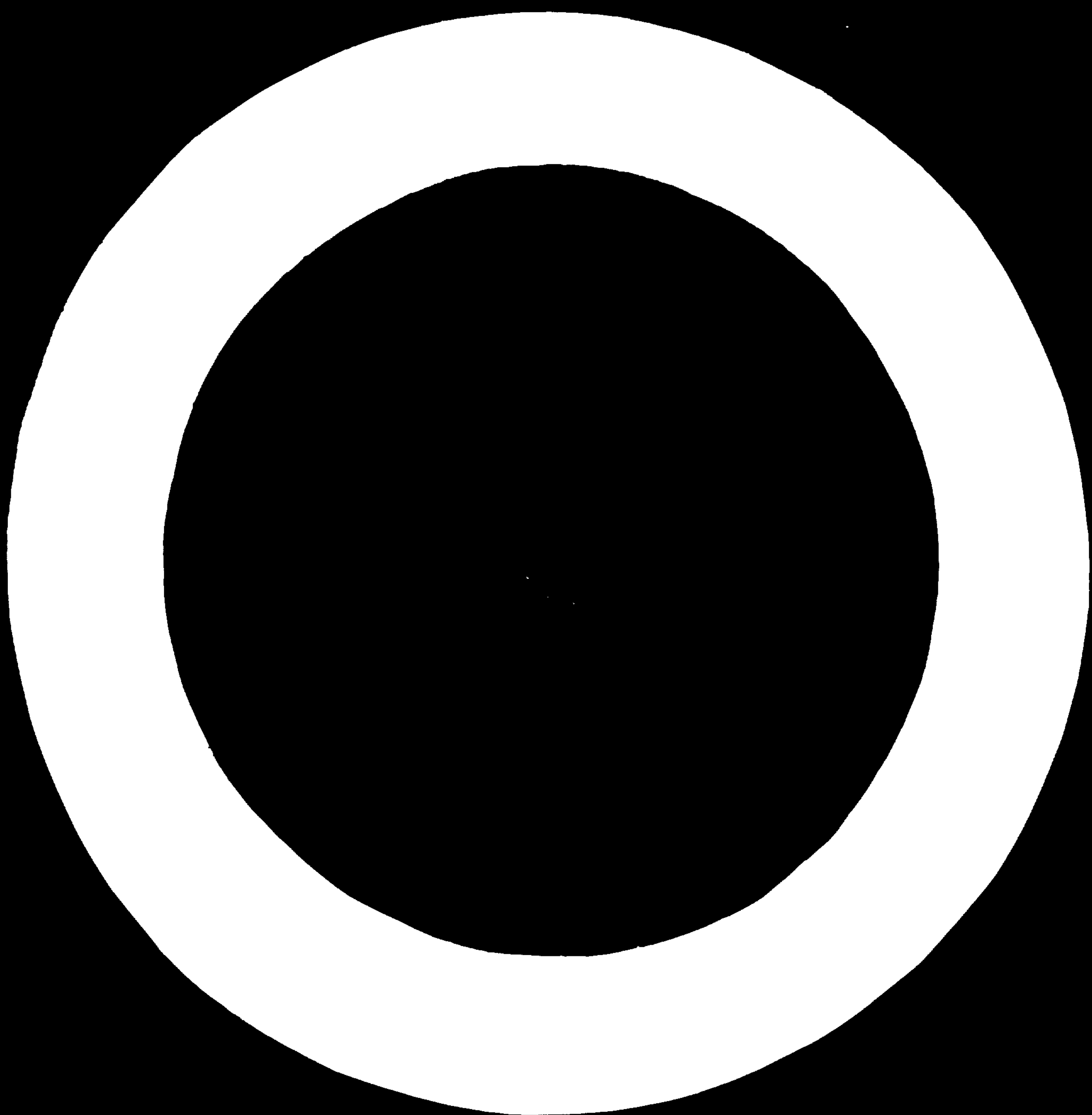

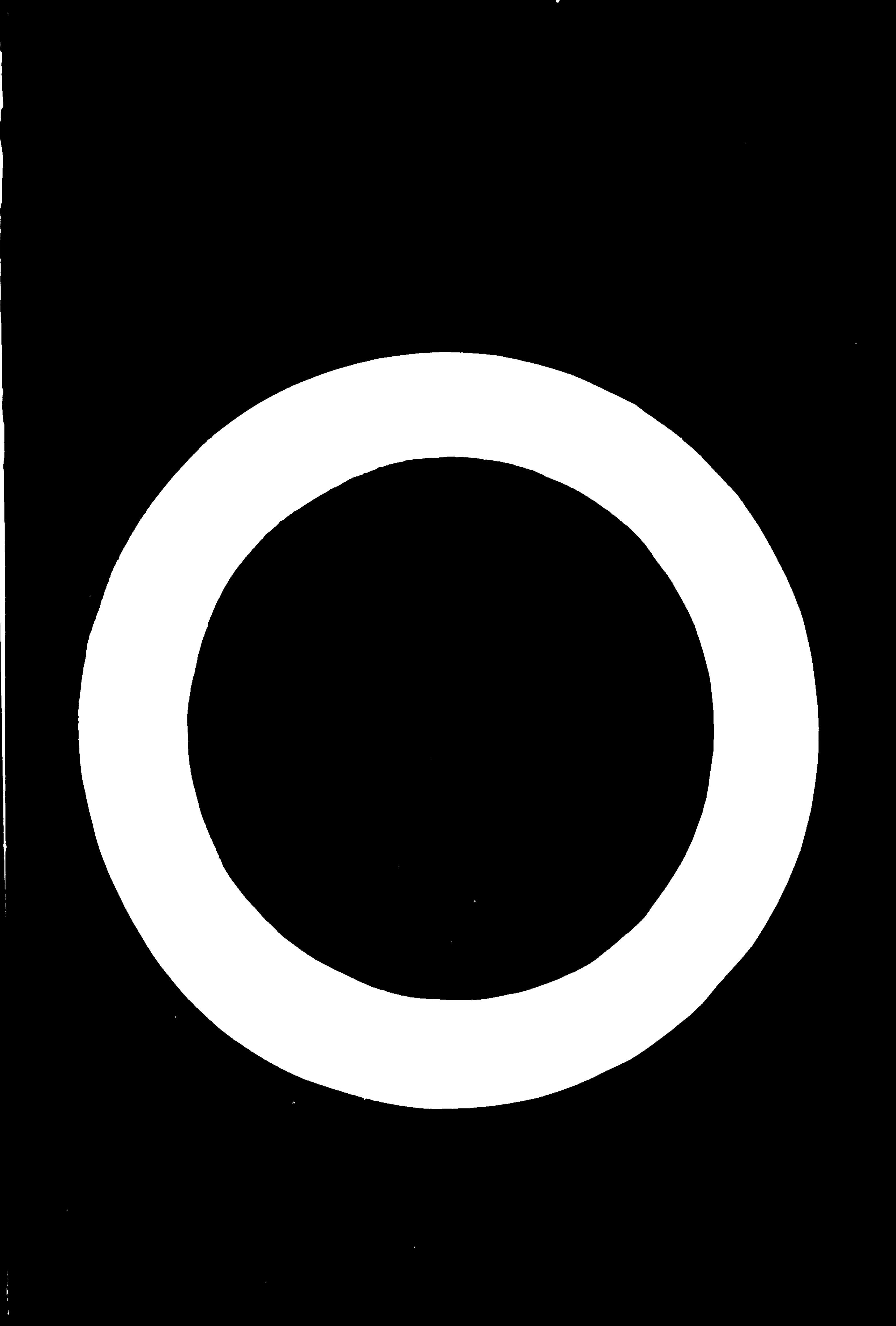

PROBLEMS OF MACHINE-TOOL REPLACEMENT

N. D. G. Mountford, Rolls Royce, United Kingdom

The maintenance of productive efficiency in a manufacturing organization is one of management's perennial problems. Machines wear out and techniques change against a background of changing product design and market requirements. The aircraft engine provides an interesting example in modern technology where profitability is very much a function of the productive efficiency of the machine tools used and the degree of skill of the labour force.

The type of machinery which is ideal for one phase of a company's growth may be a handicap when conditions change. For example, the changeover from the internal combustion engine to the jet meant the introduction of many new techniques and the evolution of new types of machine tools. Many of these had to be developed in the light of experience and with the benefit of hindsight engendered by many expensive failures. New materials were introduced which, in turn, made new demands upon machine-tool requirements in terms of surface finish and cutting speeds. A considerable advantage would have been derived if some of these problems could have been anticipated and funds for development set aside at an earlier stage.

Similar situations derive in other industries and the same difficulties are to be encountered in anticipating requirements. More often than not machine tool replacement is piecemeal. Straight wear and dilapidation results in replacement on the basis of profit maintenance while new machinery is introduced by virtue of its individual profitability on some such accounting procedure as discounted cash flow.

The need for a more general study of a company's requirements as a whole and matching of these requirements with the company's sales projections is increasing as a requirement for success. The rate of change in the world is increasing rapidly and our techniques for keeping pace in this competitive environment must also change. The days of intuitive thinking are numbered and a much more scientifically based method of laying down replacement policies must be introduced.

THE CONVENTIONAL APPROACH TO MACHINE-TOOL REPLACEMENT

The conservation of capital as epitomized in the form of machinery and equipment has been endemic in management thinking for many years. Careful maintenance and regular attention to procedures for attaining longevity have been considered as virtuous practice. In the same way, cost reduction has also played a part in the preservation of the machine tool as limitations of the actual cutting tool have slowed operations.

All this tended to make managements take the long-term view in replacement of equipment and in accounting. The influence of taxation and the manner in which governments have tried to influence manufacturers to keep equipment up to date and competitive have followed closely this conventional approach and in doing so have compounded the problem. The concern has been over the time a machine tool should last under reasonable operating conditions rather than the time it ought to last to give the best financial returns.

GENERAL ASPECTS OF MACHINE WEAR

A new machine tool will produce work of the standard for which it has been designed but, in continuous use, just how long will this continue? What are the chief causes of wear, what part of the machine is likely to suffer first and just how will this affect its profitable employment?

Naturally, before one can estimate the effective life of a machine tool, one needs to know just how long it has been in use and whether it has been confined to only a few of its functions rather than its full range. After this one needs to know whether or not maintenance has been satisfactory and the nature of the work. One would expect, all other things being equal, that a machine operating on easily cut materials might last longer than one in which the cutting forces are always at full power.

On a lathe, for example, the slide ways will wear, giving a possible misalignment to the saddle and incorrect dimensions to the workpiece. The lead screws wear, resulting in blacklash which has to be taken into account when measuring from graduated dials. Gearing systems wear, imparting vibration effects to the machine tool which then tends to resonate at lower speeds, thus producing chatter conditions which in turn can cause excessive tool wear and reduced productivity.

All of these take time and are not apparent suddenly. The inaccuracy aspects are possibly the first to be noted, since the operator has to take more and more care. Realizing this, he tends to make sure that time allowances are sufficient to cope without any reduction in his earning power. If the time allowance is not sufficient for the additional care required due to machine wear and tear, then the effects of the phenomena will be shown in an increase in corrective work and scrap parts.

Tool wear and chatter effects are not so easy to determine in terms of change, but here again the frequency of visits to the grindstone will be taken into account as well as the cutting speed limitations due to chatter, although the latter will be more apparent in some forms of work-pieces than others.

All these effects are understood, but have we any means of measuring them? How, for example, do we measure just how much work a particular machine tool has done? Do we measure total power used against time, or count the number of revolutions of the lead screw under load, or do we merely measure the machine's effectiveness in the organization by its age and assume that this is sufficient as a comparative method. All too often in formulating a replacement policy the latter method is adopted because the machine tools themselves are not fitted with any counting or measuring equipment and we have insufficient knowledge of just how or where to fit them.

Inaccuracies outside the control of the skilled operator can be assessed and to some extent corrected by maintenance, but the increased chatter and tool wear can only be corrected by removing the machine from production for a complete overhaul.

Effects of Wear on Productivity

Given the difficulties in the exact measurement of the effects of wear, one can nevertheless determine, by a simple mathematical model, what could be the effect on productivity in a factory containing, for example, 100 machine tools such as lathes.

Assuming that work conditions were constant over the period and that the loading of the machines conformed to a stable pattern, one can assess what the effects of different replacement policies would be on over-all efficiency.

If one takes a replacement policy to maintain an average life of, say, ten years, then replacement is required to begin in year eleven. If the beginning of year eleven is the starting point:

If x_r = Remainder of machines at year r,
Y_r = Replacement at year r.

Then at year r

$$(10 + r)\,x_r + \sum_{1}^{r} r\,Y_r = \text{constant.}$$

In this case

$$(10 + r)\left(100 - \sum_{1}^{r} Y_r\right) + \sum_{1}^{r} r\cdot Y_r = 1{,}000.$$

This is true until $\sum_{1}^{r} Y_r = 100$ whence

$$(10 + r)\left(100 + Y_1 - \sum_{1}^{r} Y_r\right) + \sum_{1}^{r} r\cdot Y_r = 1{,}000 \text{ etc.}$$

It can further be assumed that the deterioration in the machine's behaviour can follow either a stepped pattern as in figure 1 or a constant linear form as in figure 2.

If in the former case, one considers that the machine tool will behave as efficiently over the first ten years as when it was new (a state of affairs that all machine-tool manufacturers would like to think exists), then there will be a fall-off over the next five years to 75 per cent. The efficiency of a machine may be defined as the number of good parts it is capable of producing over a given period of time, for example, a month. This takes into account all the delays and difficulties comprised by operator fatigue, maintenance and rework, etc. This 25 per cent loss in productivity would be due mainly to the effects of wear on accuracy that could not be put right by maintenance, and the increasing possibility of breakdown. The second fall-off, assuming no general overhaul, would result from increased vibration and chatter, inhibiting the use of the machine for high quality parts due to its tendency to produce poor surface-finish effects.

In the second case, the deterioration shows as a gradual effect right from the beginning. A rate of 2 per cent brings the machine's efficiency down to 50 per cent at the end of twenty-five years.

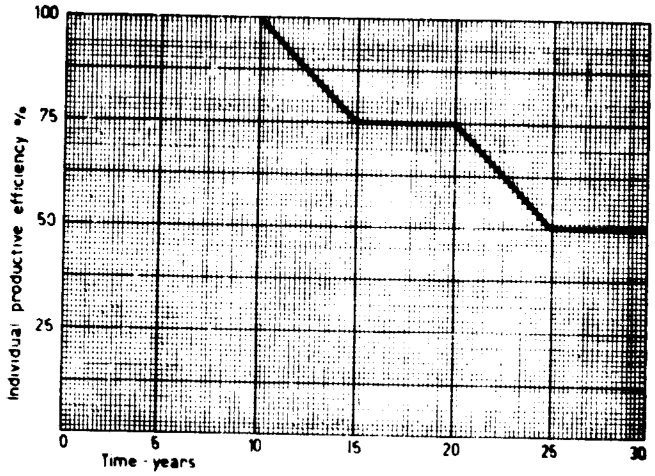

Figure 1

Stepped Deterioration Function for Individual Machine Tools

In actual practice these effects may not be quite so drastic and would in all probability be a mean between the two, but are represented in this way for simplification of the mathematics. For the purposes of this representation and in the first instance, the replacement machines are to be of the same type as the replaced machines.

The number of machines to be replaced are considered in three distinct policies:

(*a*) A ten-year average life policy;
(*b*) A 5 per cent replacement policy;
(*c*) A 10 per cent replacement policy.

Each begins in year eleven. Figures 3 and 4 show the effects of these replacement policies on the overall efficiency of the factory for the corresponding form of the machine deterioration curves. From these curves it can be seen that the 5 per cent replacement policy ultimately results in stabilization of efficiency at a similar level to that of the ten-year average policy, but this

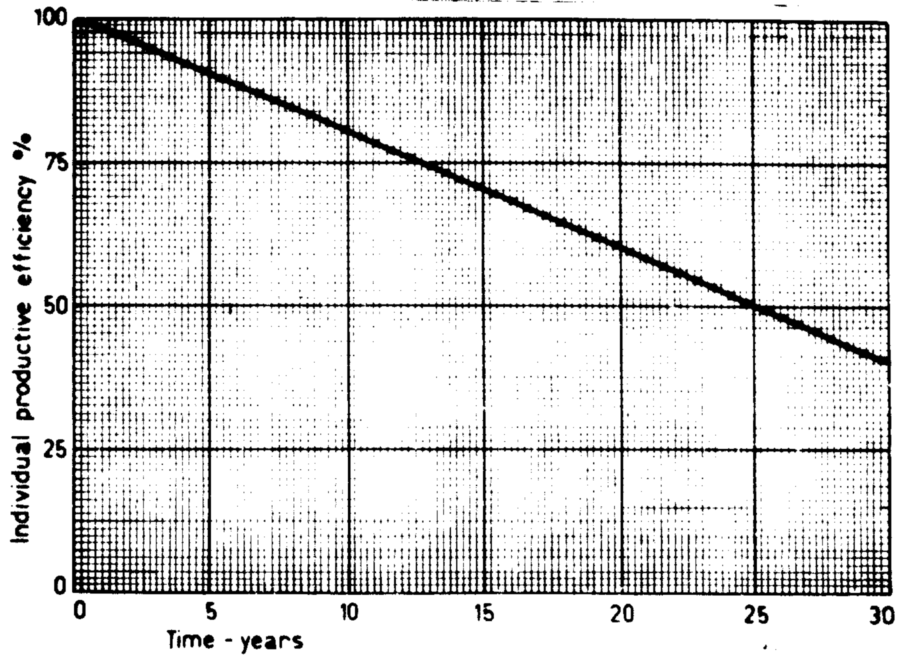

Figure 2 STRAIGHT-LINE DETERIORATION FUNCTION FOR INDIVIDUAL MACHINE TOOLS

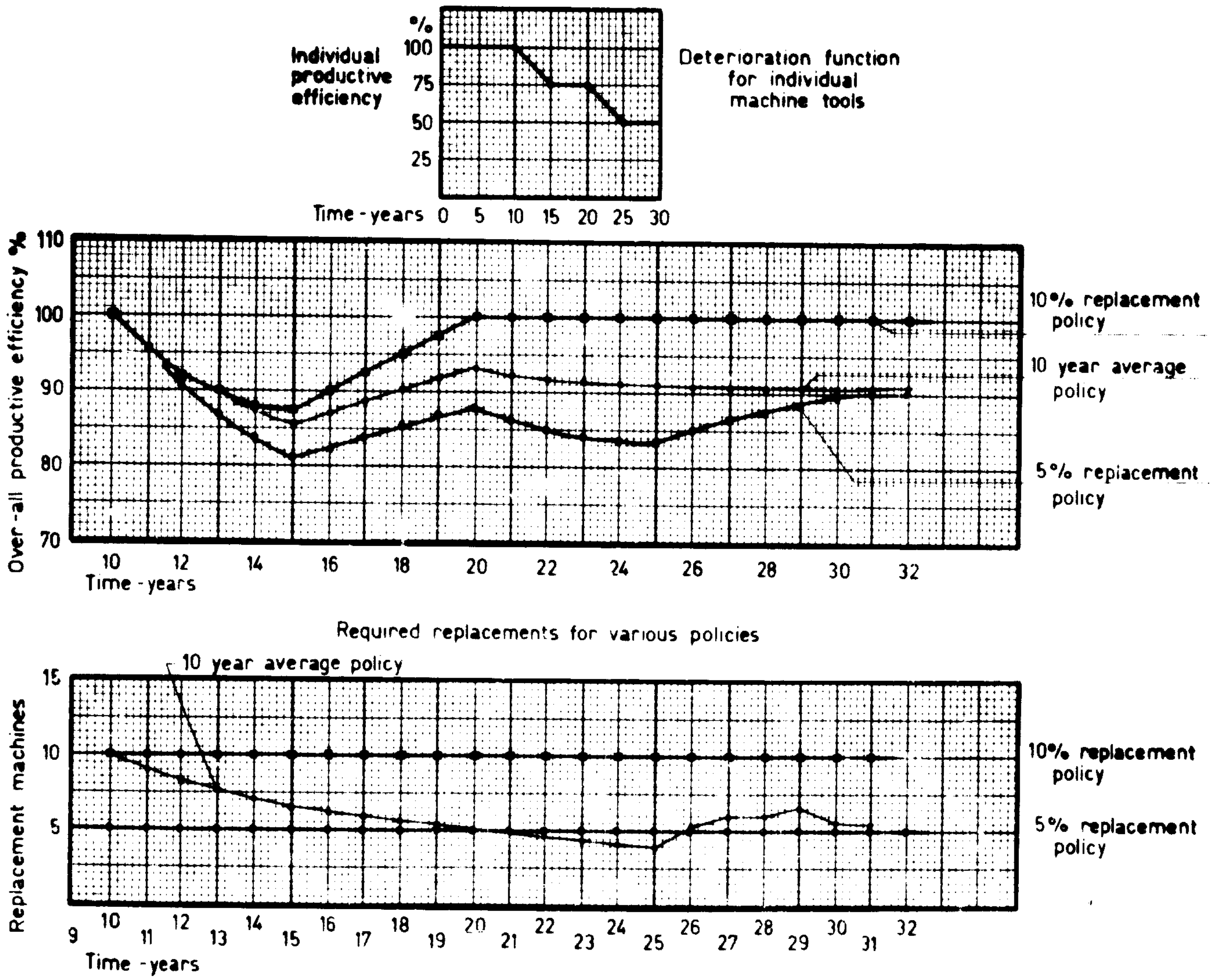

Figure 3 —VARIATION OF OVER-ALL PRODUCTIVE EFFICIENCY OF CONFIGURATION FOR VARIOUS REPLACEMENT POLICIES WITH STEPPED DETERIORATION FUNCTION

would take several years. In the case of the constant linear deterioration, the decrease in efficiency is much greater but the pattern of recovery is similar.

It is apparent that for any orderly replacement policy there will be a transient condition where over-all productive efficiency varies with time. Subsequent to this, a steady-state condition is realized where the over-all productive efficiency remains constant. The length of this transient stage, and the ultimate level of the stable over-all productive efficiency depends on:

(*a*) The condition of the machine-tool configuration before the replacement policy is begun, i.e., age and wear of the machines.

(*b*) The quantitative level of the replacement policy;

(*c*) The type of replacement policy.

unchanged and machine tools of a similar nature replace those thrown out by use; it can be shown that to restore efficiency completely under these conditions one would have to replace some 49 per cent of them over a year or so.

For given conditions of deterioration, the quantitative level of replacement must be governed by the estimated savings from restoration of productive efficiency offset against the depreciation and capital cost of new equipment.

As overhauling may not completely restore a machine tool to its former efficiency, it may nevertheless affect the deterioration in efficiency, and if one assumes the linear deterioration effect together with an overhaul restorative effect as in figure 5, one can get the comparative over-all factory efficiency curves as in figure 6.

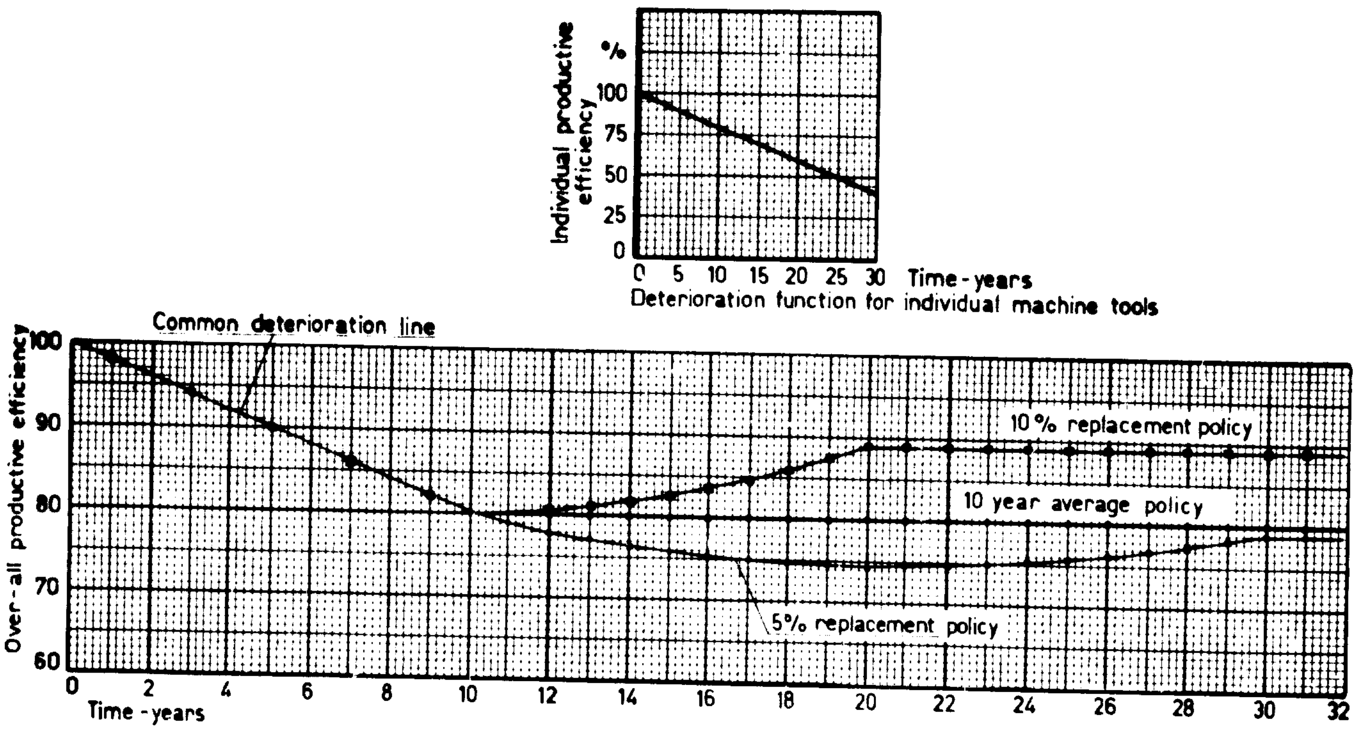

Figure 4

VARIATION OF OVER-ALL PRODUCTIVE EFFICIENCY OF CONFIGURATION FOR VARIOUS REPLACEMENT POLICIES FOR STRAIGHT-LINE DETERIORATION FUNCTION

In the case of most factories, the imponderables are:

(*a*) What is, or was, the state of the original configuration?

(*b*) If an orderly replacement policy is in being, where are they along the transient curve, or have they reached stability?

Having reached stability and realizing the loss of over-all efficiency, what corrective measures can be employed to bring the system back to its former competitive position?

FACTORS DETERMINING THE REPLACEMENT POLICY

The hypothetical conditions just indicated assume that the basic technology on which the factory works remains

One would expect that the results of overhaul would not necessarily restore a machine completely to its former efficiency, also that the frequency with which overhauling becomes necessary would increase with age.

The cost of overhaul and just what is required has to be assessed against the type of work to be carried out on the machines. In fine-finish accurate work, one would need to spend more money on remachining the slide ways as well as replacing the gears and lead screws than for work of a rough nature. In the latter case, time between overhauls would be much longer. More often than not, however, machines are expected to perform both rough and finish machining, in which case the latter conditions determine the extent and cost of the overhaul.

Policy will obviously be determined by the nature of

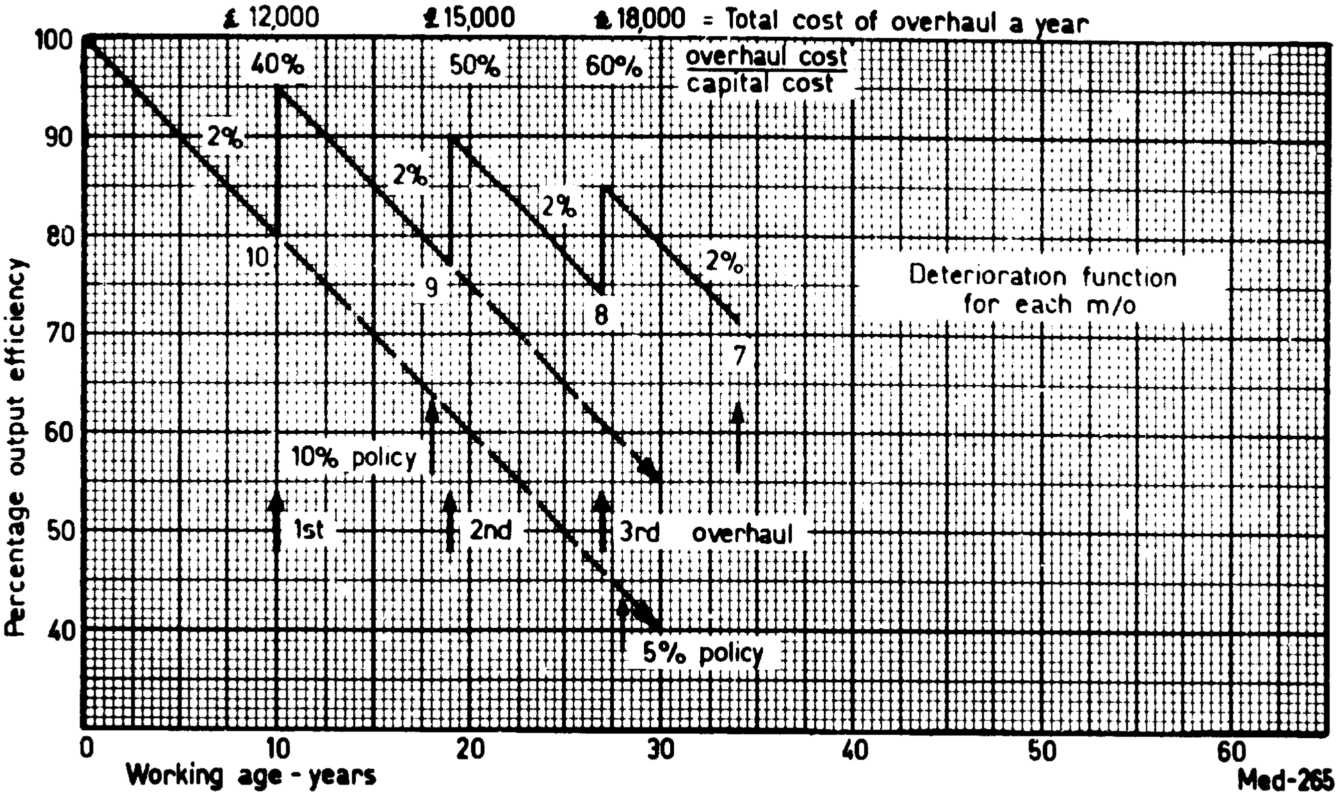

Figure 5

MACHINE-TOOL REPLACEMENT POLICY

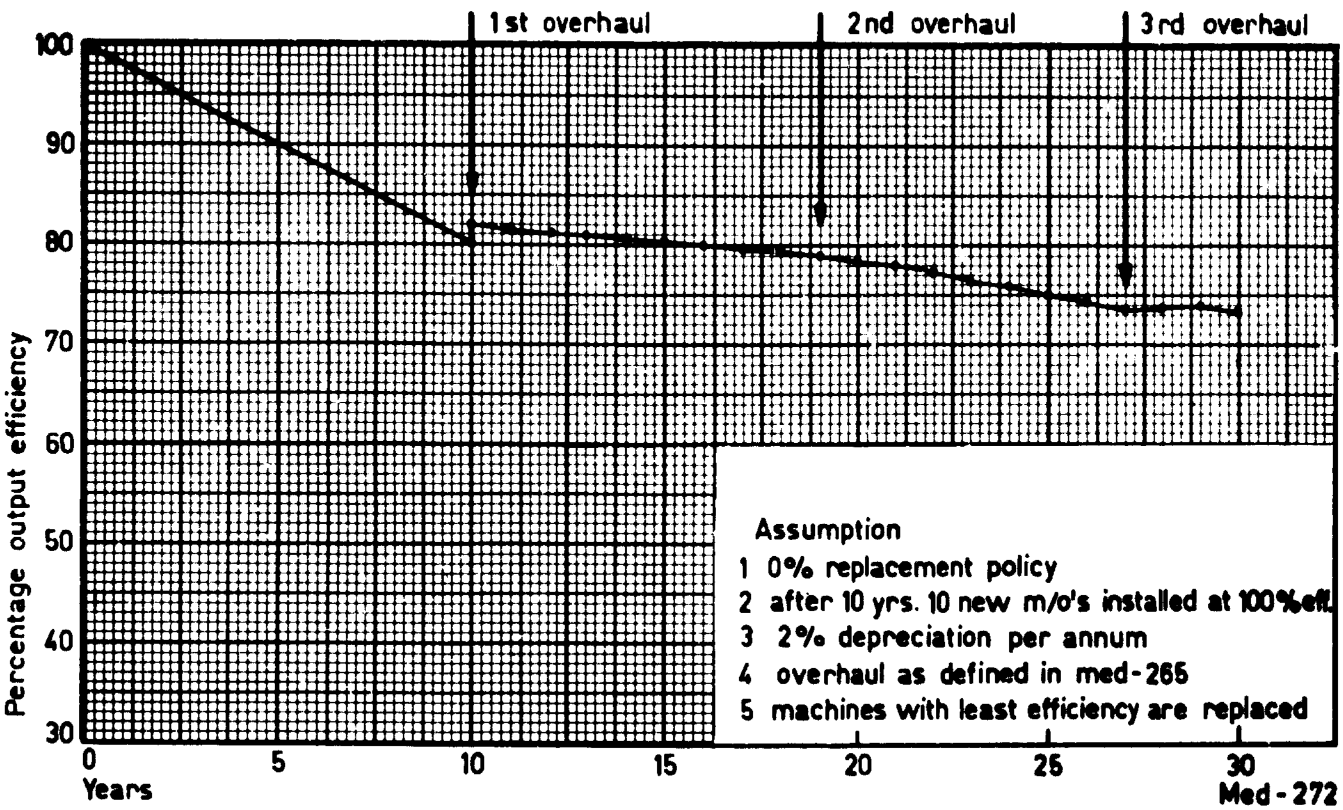

Figure 6

MACHINE REPLACEMENT POLICY

the work in a factory, and this may well change radically over a period of some twenty years.

The transition from small quantity, small-batch work in great variety to large volume production will give rise to the transition to full automation as an economic necessity, but where batches are to remain small without any concession in terms of reduction in variety or increase in quantity, then the changes will mainly be in techniques or in the individual design of the machines. The over-all policy will be implemented as a judicious mixture of replacement by new machines of improved design and efficiency, new techniques applied to old machines to improve their productivity and accuracy, and the renovation of old machines.

Figure 7 shows the effect on factory efficiency if the average efficiency of the combination of new machines, renovations and new techniques exceeds that of the original machines when they were first installed. From this it can be seen that to make any rapid effect the required average improvement in efficiency must be quite high on the basis of 5 per cent replacement if the condition of the original machines has been allowed to deteriorate to the 80 per cent efficiency level. In all probability, however, the changes in technique could be applied to a large number of the older machines without too great an increase in capital cost. At the same time, however, it will be necessary to replace the older worn-out machines on a basis consistent with the money available and the best efficiency.

The most important consideration is that the improved productivity brought about by the replacements should give rise to improved profitability. The capital cost of the new machinery must be amortized without an increase in the cost of manufacture of the components.

Figure 8 shows the curve for the 2 per cent deterioration and the effect of injecting new machinery at the ten-year stage of 120 per cent average efficiency on a 10 per cent replacement basis. Figure 9 shows a similar set of conditions but with the replacement machinery assessed at 180 per cent

The cost of parts produced over the period is represented by the bar chart. This cost can be graphed under three main headings: Direct cost of labour, standard overhead charges such as rent rates, heating, lighting supervision, maintenance and administration charges, and the amortization of the capital equipment. Over the first period, the productivity diminishes, increasing labour costs. The greater production time means that an additional overhead must be carried by the part, that is to say, time on the shop floor proportionally increases the amount of rent, light, heating and supervision. In the same way, the amortization rate for capital equipment must fluctuate as repayments can come only through sale of the produced articles. As manufacturing time lengthens there will be fewer of these and hence the amount of money which must be levied against each article will have to change.

At the end of ten years, the first machine will be paid for, theoretically reducing the cost of manufacture but, from this point, the cost of the new machine must be

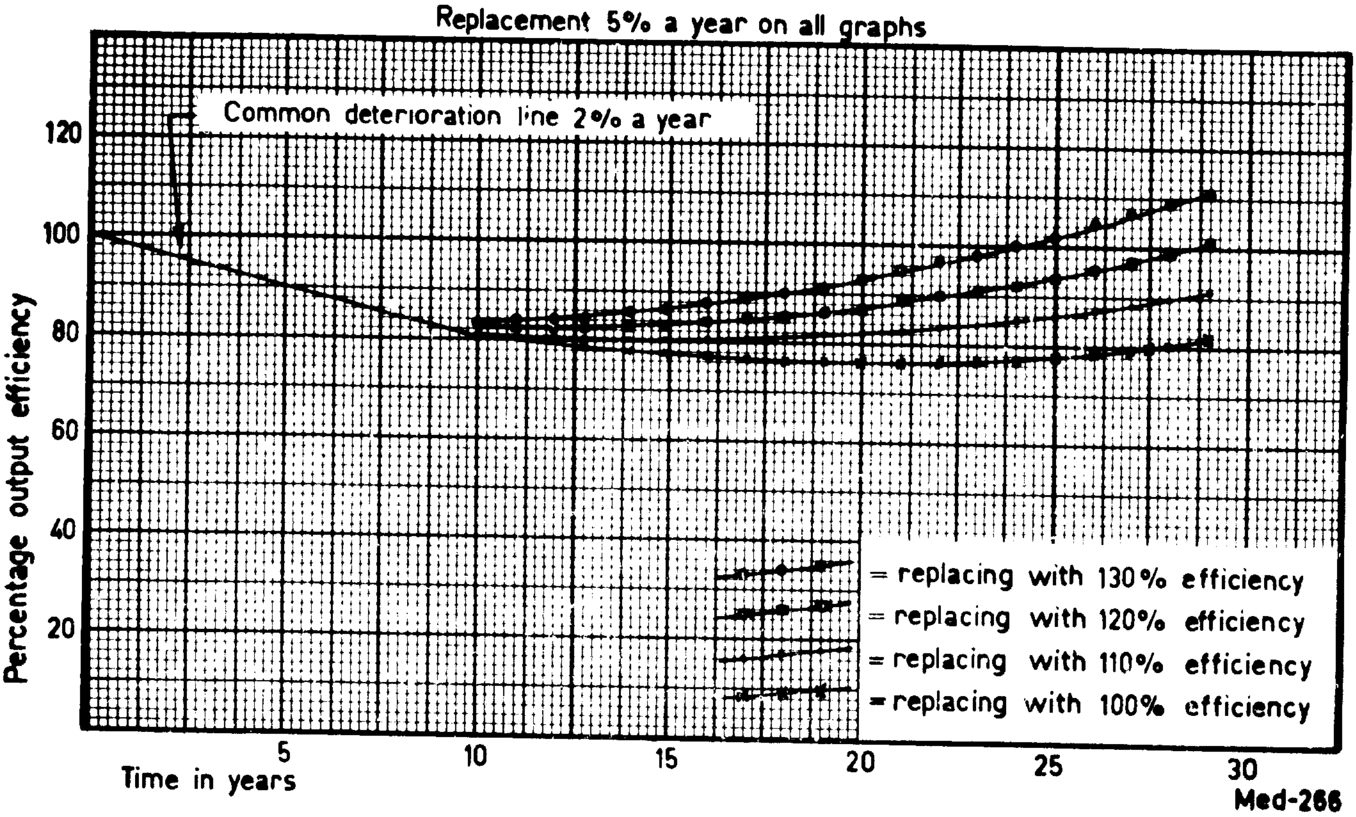

Figure 7

MACHINE-TOOL REPLACEMENT POLICY

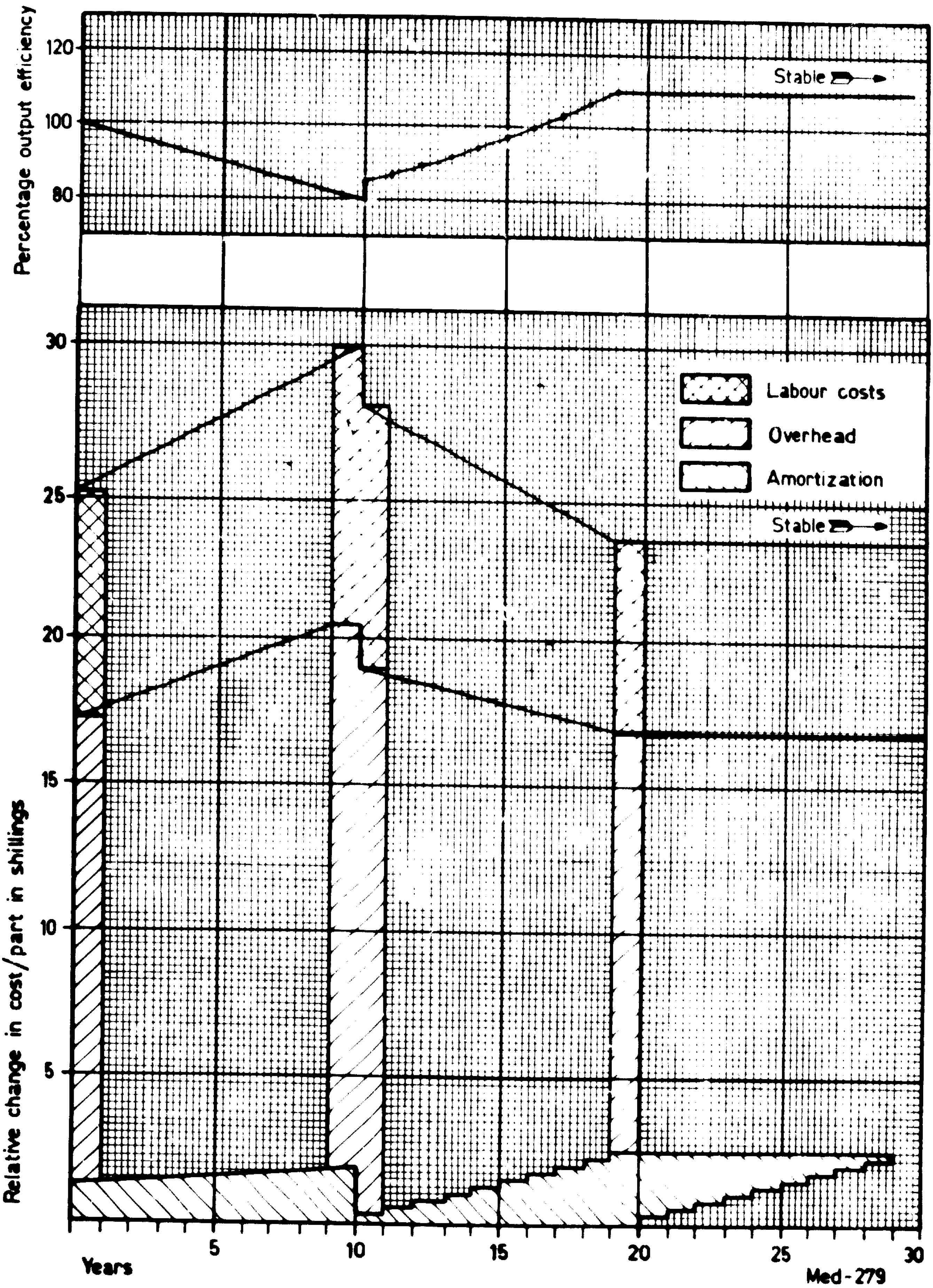

Figure 8—TEN PER CENT REPLACEMENT POLICY WITH AVERAGE OUTPUT EFFICIENCY OF 120 PER CENT

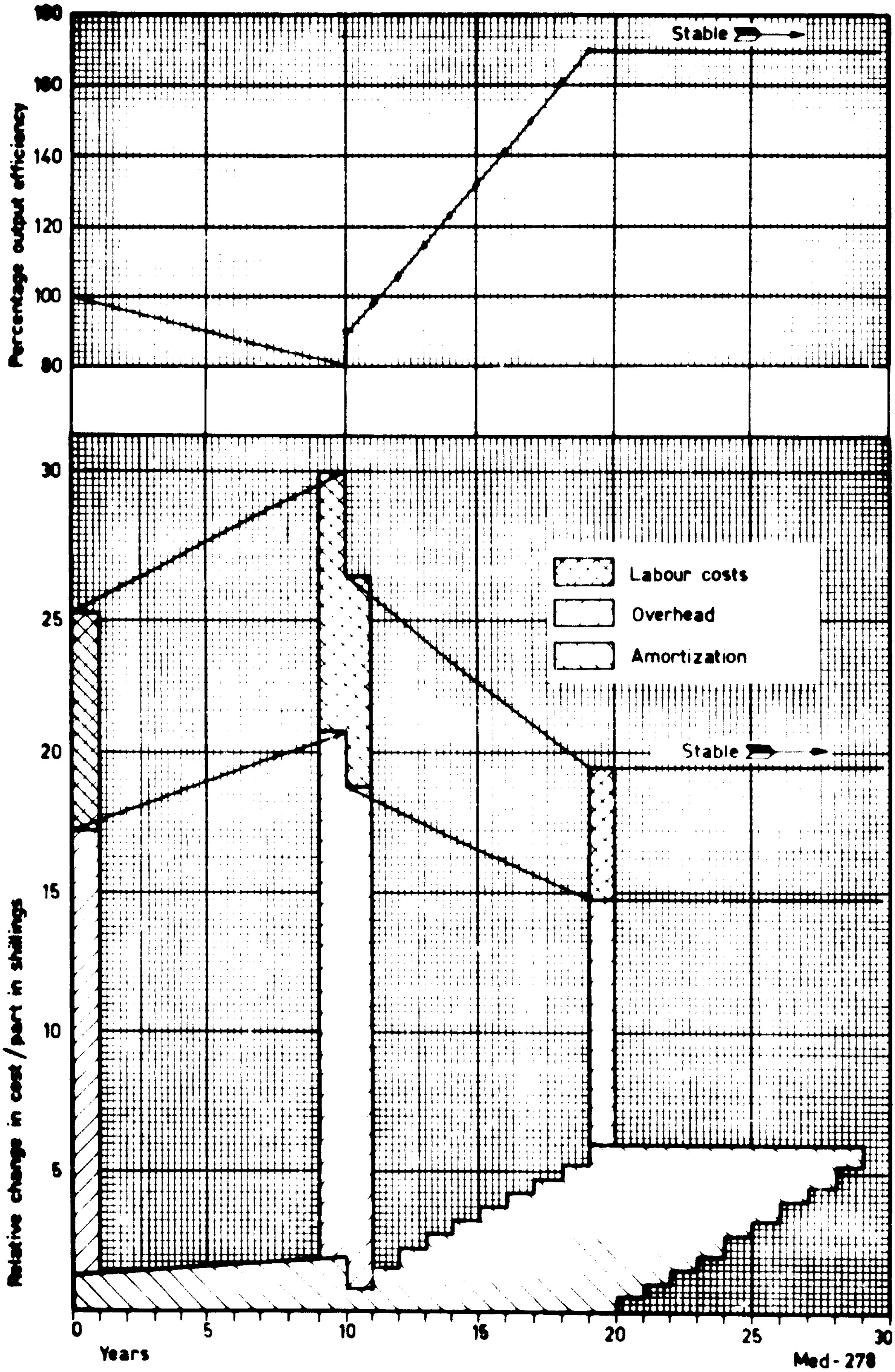

Figure 9—Ten per cent replacement policy with average output efficiency of 180 per cent

allowed for and will grow each successive year. A steady state condition will arise ten years from the start of the policy if yearly investments are made and are amortized over ten years.

Efficiency rises with the introduction of the new equipment and more parts will be produced over a given period of time. The reflection in the component's manufacturing cost should restore the profitability to its former level, but unless a lot of capital can be found it can be seen from the diagram that restoration of profitability can be a slow process if achieved solely by the introduction of new machinery. It becomes obvious that changes in technique must be introduced to restore the efficiency of the large number of older machines and that the changes must be less expensive.

New machines

Faced with machine replacement, the types of machine must be analysed to ascertain the gain for a given capital outlay. The trend has been towards the use of discounted cash flow technique in which the time value of money is used to measure the return on the capital invested. The rate of return in terms of interest on the capital invested in the machine tool can be measured against the returns on a similar sum invested in the best of other ways. If, for example, we look at lathes, the scope is wide and a review must ascertain the correct function for the machine. Basically, lathes can be split into three main categories: standard hand-operated machines, programme controlled machines and hand-operated machines fitted with aids such as datum stops in conjunction with off machine setting. The choice of type is, therefore, dependent upon batch size, setting time, operating time and capital amortization. This is shown in figure 10 where the cost per part, depending on batch size, is shown with these different types of lathes, taking into account efficiency factors which will vary with each type, and a machine life of ten years.

It can be seen that it would be an unwise policy to replace existing standard hand lathes with like machines, for the machine with fixed stops and off machine setting is cheaper in operation up to batch sizes of seventy-five and the programme control lathe is cheaper when the batch is more than seventy-five parts. Comparing the standard hand-operated lathe and the programme lathe the cross-over point is twenty parts.

The examples guide replacement policies, the need to increase the efficiency of the standard older machines has been shown to be essential and to this end there are now many new aids and techniques on the market. One of the most inefficient parts on a machine tool is the positioning of the slides due to the use of graduated dials in conjunction with lead screws with the possibilities of misreading and miscalculation because of backlash. The utilization of digital read-out systems, which do not rely on either of these two factors to give positional accuracy, should be employed wherever possible. The type of read-out and relative cost depend upon the degree of accuracy required. For very accurate work, the use of such systems as the Ferranti or Sogenique and others could be applied. The main disadvantage of the electronically displayed read-out is that the last digits alter at such a great rate on traversing to a given position that it is difficult to approach the final setting at anything but a very slow feed.

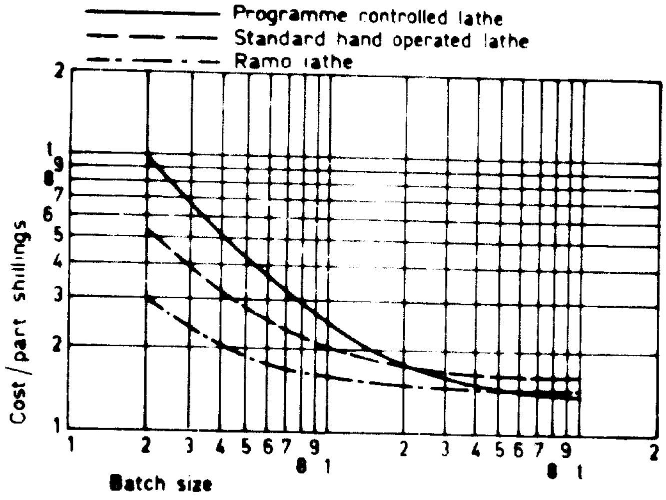

Figure 10

Cost per part on different machines and varying batch sizes

This results in a considerable slowing up in the operation. These systems cost about £400–£500 an axis, but recently there have been less expensive developments in which the final readout is a pointer and dial system. Operators prefer this approach and can work such a system almost as fast as one controlled by tape.

Such units can be fitted to any machine tool. It has been shown that with such as the Ferranti system applied to lathes it is possible to turn diameters to within 0.0001 in. and with the dial indicator follower fitted on two axes, a boring machine could bore holes to within 0.001 in. of true position at twice the conventional speed.

Reverting again to lathes, there are many other aids available, such as quick-release tool posts coupled with off machine setting, the use of throw-away tip tools, etc., all of which increase use of the machine and thus productivity.

In figure 8 the replacement machines must give efficiency of 120 per cent. This could in practice be achieved by the purchase of one or two of the costly semi-automatic machines of high efficiency, plus a higher proportion of standard machines fitted with such aids as the digital readouts. The proportions of each would need to be carefully tailored to the work and the capital resources. An approximate relationship can be obtained between the efficiency of a machine, or group of machines and capital cost. This is shown in figure 11 as a relatively broad band within which there will be variations attributable to quality, ancillary features and so on. If the machines are not employed at their optimum, for example, if a programme-controlled lathe is used on too small batch quantities or if a large number of parts are produced on a machine more suited to small quantities, then the relationship will tend towards that enclosed by the dotted lines.

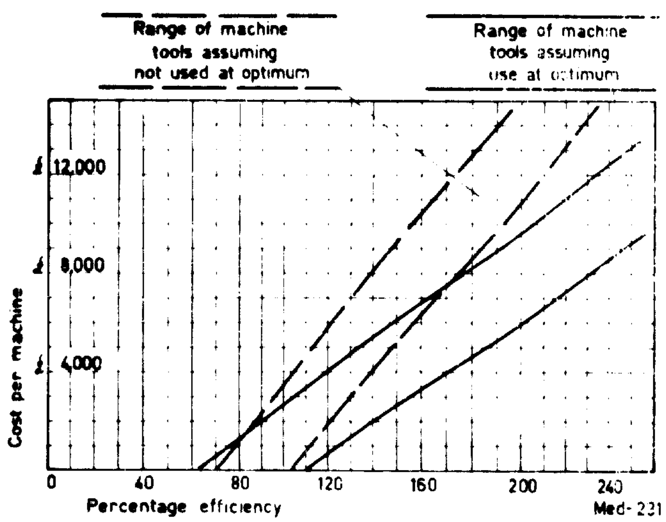

Figure 11

EFFICIENCY v. COST FOR LATHES WITH 6 IN. AND 8 IN. SWINGS

Given an unlimited market and capital from sources other than profit it is obviously better to go for the more sophisticated machinery (figure 9), but all too often these conditions do not apply and ingenuity must be used to effect the optimum result.

FULLY AUTOMATIC MACHINES

A significant point about figures 8 and 9 is the effect of overhead costs. These inevitably tend to rise and magnify the production cost changes from alterations in actual machine efficiency. The greater they are the greater will be the effect. Where the work is of a complicated nature, these overhead costs can be high due to the need for the design and manufacture of jigs and fixtures.

This is particularly true in milling, drilling, tapping and boring for such components as pump bodies, casings, connexions, etc., and there is a need for machines which can operate efficiently without these extra aids.

Of recent years there have been many developments of sophisticated machines capable of fully automatic action and of such accuracy that they can perform operations without expensive fixtures, the Milwaukeematic and C.S.P.matic being two well-known examples whose performance is fully documented.

The main drawback to such machines is twofold: high cost and relatively slow production rate. The latter may sound anomalous in view of the fact that for individual components the actual time of manufacture is much less than for the combination of standard machines and fixtures. Set-up times are less and much dead time reduced as many more operations can be carried out from one setting on a simple fixture.

There is, of course, the added cost of making the tape, but this is counterbalanced by a considerable reduction in fixture costs. The main problem is the machine's capability of producing a number of components in a given time. A spindle can only do one operation at a time, whereas with the standard procedure a number of simpler machines together with their fixtures can be operating. The penalty in the case of the standard machines, apart from the fixture costs, is the increased number of settings and the difficulty of making the parts flow through the factory without congestion.

The decision on installing such highly efficient machines will depend upon the nature of the work and production rates. For low production rates on highly complicated parts, but where the amount required is high, there is a case for the completely automatic machine

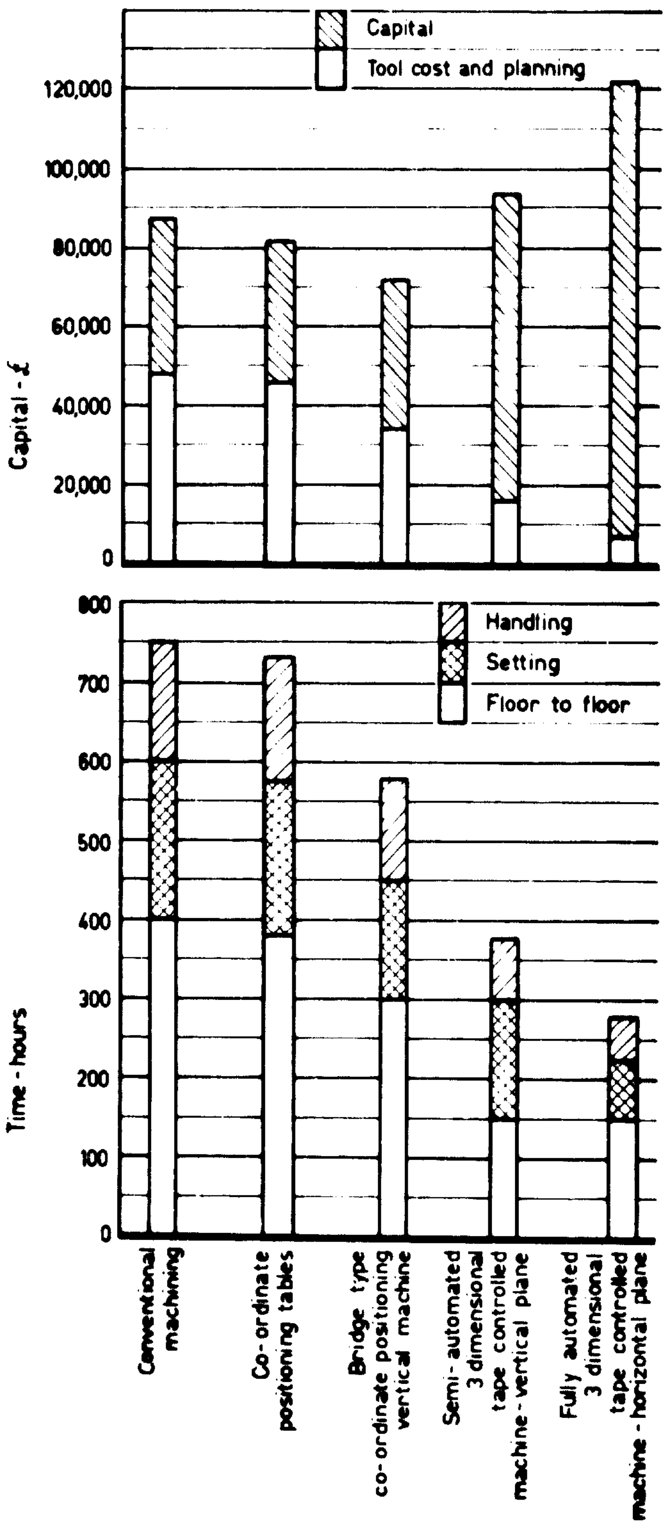

Figure 12

tool, but where relatively high rates are a requirement, a combination of less sophisticated but nevertheless automatically controlled machines would appear to be better.

This can be illustrated by a study of the manufacture of jet engine parts using machines of varying sophistication, from the standard machines with fixtures to the fully automatic such as the Milwaukeematic. Trhe ba chart in figure 12 shows the costs involved in manufacturing two sets of twenty-five different components a month. The relative reduction, in fixture and operating costs, from the standard conventional methods can be rates of production, the manufacturing times by conventional practices are lower because of the lower setting costs but, with the fully automatic machines, over-all cost is extremely high owing to their individual cost and relatively slow production rate.

In figure 14 the number of components is shown for a given rate of production. Here the cost of conventional practice is more expensive than the fully automatic approach but in each case the combination of machines, *D*, gives the best result.

In choosing from a group of such machines, the tape controlled horizontal boring machine and vertical bridge

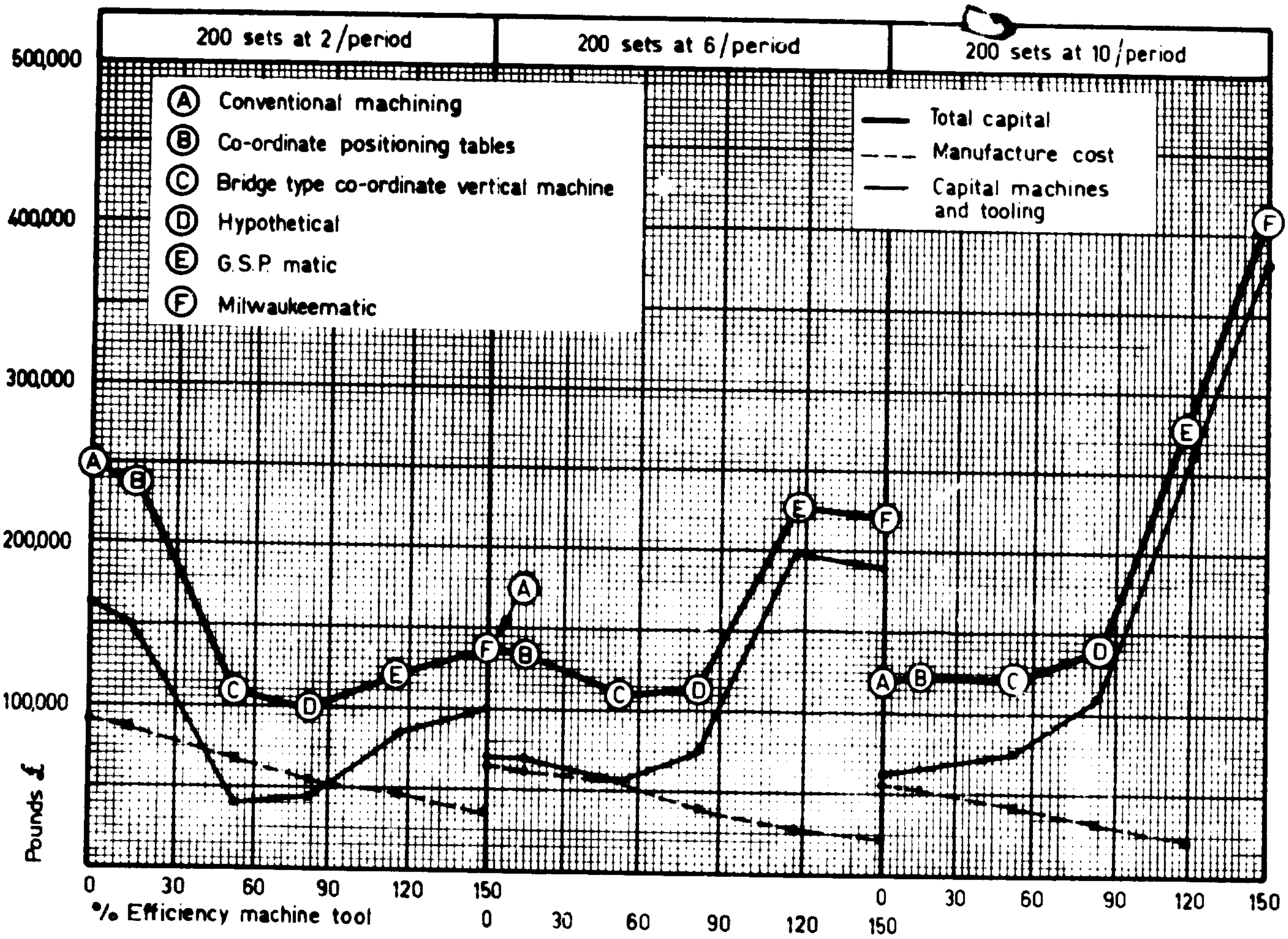

Figure 13

taken as a measure of the relative efficiency of the systems and can then be used to compare the systems for different conditions of operation. In figure 13 is shown the same groups of costs illustrated graphically with the horizontal axis showing a measure of the over-all efficiency of the systems. The hypothetical system *D* is a combination of machines both horizontal and vertical selected to match the proportions of operations in the two planes with the horizontal machine giving greater accuracy. A study of the parts revealed that only 20 per cent of the operations needed accuracies better than 0.001 in. of true position. The heavy lines on the graphs indicate total cost, assuming given rates of overhead and tool charges. With high type with programme control are examples which appear to give the right combination of accuracy, facility of operation and cost.

The Dixi tape system has the added advantage that at any time a cross check can be made using the optical system and that the tape can be made while machining the first component. This has the advantage of further reducing the overhead costs. (It is interesting to note that similar systems are being applied to other machines.)

Jigs and fixtures are one aspect of overhead cost; another is simplification of the manufacture procedure. Less effort from ancillary personnel such as labourers, storekeepers, supervisory and checking staff as well as

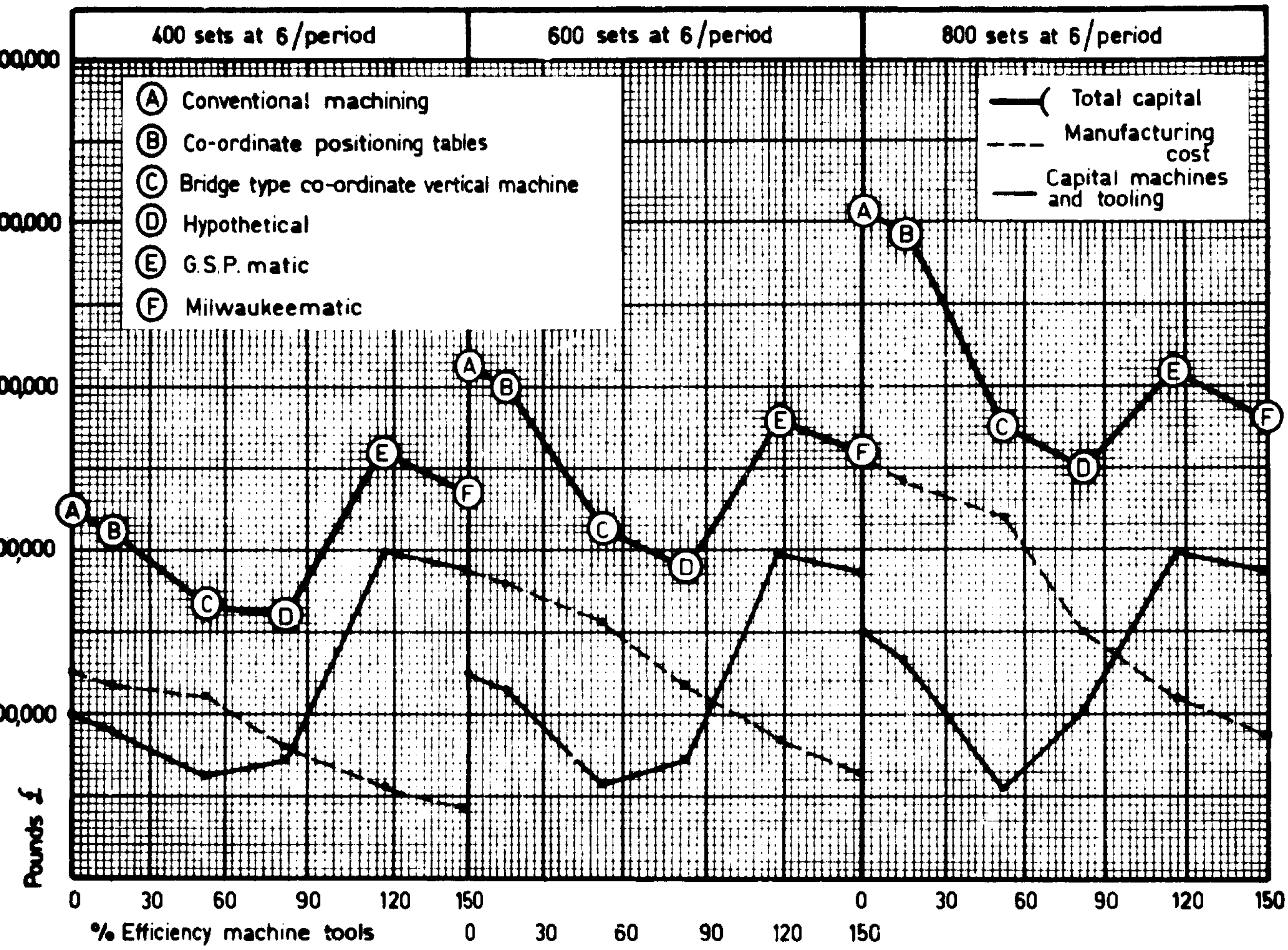

Figure 14

inspectors will be required together with the reduction in work for a given output.

When choosing the particular type or types of machine as replacements from this category one must again give careful consideration to the exact nature of the work in hand and the possible future trends from the point of view of quantity, variety and rates of production. Such machines would initially be used to augment existing equipment, tackling the short-run or prototype work, but ultimately their scope would widen.

Observations derived from conventional practice

The figures and examples form only a very limited outline of the problem. They provide a basis for study in order that the problems can be delineated with greater accuracy.

The true effects of machine wear on the productivity of a factory are not easy to determine. Ostensibly, time studies result in rates of manufacture which do not change and theoretically the cost of a particular part should not alter, but with machine wear must inevitably come increasing difficulty in maintaining standards of accuracy and quality. This difficulty is bound to be assessed by the operator and taken into account when the time for subsequent new parts is being considered.

This deterioration in efficiency may be masked by the introduction of new materials about which there is insufficient data as to their machinability. It will be a very gradual effect very much related to the nature of the work and output demands. Its effect, when translated into terms of profitability, will be magnified since, as a direct result, the sale of a reduced number of articles must carry the overhead burden.

From these observations stem the problems of assessing machine wear and measuring the over-all efficiency of a factory system. Much work has been done in the field of planned maintenance to overcome the productive loss caused by machine breakdown, but there is the need to be able to measure more accurately just how the machine behaves in relation to the work it has to perform. The accuracy with which the parts can be produced can be checked with relative ease, but the effect of wear which results in the increased tendency towards vibration and a deleterious effect upon cutting-tool life and surface finish needs further study. Tests need to be devised which will demonstrate the condition of the machine in this respect and records of this nature should determine the programme for planned maintenance. To this knowledge must be added that of the better understanding of the machining characteristics of the materials from which the parts are to be made. Tool wear and horsepower measurements enable an accurate assessment to be made as to whether a particular machine is performing at the optimum conditions possible. Statistical analysis of data of this kind should enable management to assess the over-all mechanical efficiency of its productive effort.

A NEW APPROACH FOR THE PRODUCTION AND SALES ENGINEERS

The conventional concepts reflect the narrow views of these, intimately connected with the daily running of productive machinery, whose horizons are bounded by the factory walls within which they work. All too often their communication with other departments, such as sales, is limited to receiving orders and to the verbal skirmishing between departments as they attempt to satisfy the conflicting interests of cost and customer priorities. General management, in attempting to be a referee between these factions, is all too often obsessed with cash-flow problems and adopts a negative *laissez faire* attitude, neither stimulating production to use and replace machinery in an optimum fashion to meet demands nor preventing the sales departments from making subjective assessments of the value of satisfying customer demands for special orders or obtaining the best product mix.

This state of affairs develops as the company grows. In small companies the owner, or entrepreneur, wears several hats. Very often he is engineer, salesman and production engineer and can decide on the basis of his knowledge of all three departments the best course of action. As the company grows, these functions reach magnitudes which are beyond the control of any one man and the firm splits into departments. The continued growth of the company sees the strengthening of the boundaries between the departments and a general lack of understanding of each other's problems. The production team has no time to get out and observe at first hand the type of work which is being carried out by its customers or the various ways in which profitable help could be given. The salesmen on the other hand are not always chosen for their technical ability. They often miss opportunities and make unreasonable demands with regard to time in solving production problems.

Both sides must have a wider knowledge of the complete set of problems facing a firm if the correct policies on replacement of company machinery are to be adopted. Communication techniques must be evolved which are understood by both sides. A language which is comprehensible to both must be formulated. This language must obviously be an improvement upon that which has been used up to the present, that is, standard accounting procedures.

ACCOUNTING PROCEDURES

The accountant attempts to satisfy the requirements of management, production and sales for control information by collecting all data relating to expenditure and then presenting it in a form which purports to show the profit or loss situation at the time of data collection. The departments then measure their performance against this information. This is obviously a vignette, a cross-section of the situation at a given time and may present a static and entirely erroneous picture.

Business is dynamic and constantly changing and companies are constantly adapting to a changing environment. One can use many illustrations to show just how rapidly our world society is changing. Take, for example, the speed with which man can travel.

If plotted from the first century A.D. to the present, one can see that up to the end of the eighteenth century little more than fifteen miles per hour was possible. During the nineteenth century, with the advent of the locomotive, speeds in excess of sixty miles per hour became commonplace. The introduction of flying and the internal combustion engine made a further great advance possible in the first half of the twentieth century and now, barely a decade into the second half of the century, we treat as commonplace the fact that man can orbit the earth at 18,000 mph. This does not mean that our present progress is reaching an asymptote but it does show that the increasing pace of our technological development is making it difficult to predict the future as accurately as we were able to do in the past.

If we consider the curve showing man's ability to travel at speed against time and one considers the situation in, say, the sixteenth century, progress at this stage was slow and almost linear. It would have been possible in the early years of Elizabeth's reign to predict what England would have been like at the end of the century. The same was almost possible in the late nineteenth and early twentieth centuries, but now we are on that foot of the curve where change is becoming rapid. We tend to project our experience in the past along the tangent to this curve and inevitably are surprised when we find that the advances are much greater than expected. This state of affairs will inevitably get worse and we will find ourselves undershooting our targets by greater margins unless we can develop better methods of prediction and be able to assess rates of change with greater facility.

The present accounting methods will not fulfil these needs and a more scientific approach will have to be devised.

As a first step, it will be necessary to rethink many of our ideas. The salesman, the production engineer and the accountant have very different ideas of what a company may be trying to do. The salesman feels that he is selling a service; this may be in the form of a special product, but he regards as paramount the needs of his customers and the servicing of their requirements as the first duty of his firm.

The production engineer has to make pieces of intricate shapes and high quality. He has to keep his machines running at minimum cost, or so he thinks.

The accountant is obsessed with return on capital and regards people and materials as items which can be reduced to purely money values and juggled accordingly. Fifty people are fifty times their weekly wage as far as he is concerned, but the production engineer will see in each a different potential for productive effort. The salesman views them as remote beings who never produce enough and are always the root cause of difficulties with his customers.

In essence, a manufacturing company is selling labour. It uses materials and machinery and adds to the value of the initial raw material a margin sufficiently large to pay the labour and auxiliary costs as well as to provide the margin of surplus to make the concern viable. By viable is meant that the returns on the initial capital are large enough to maintain growth and refurnish this capital at a rate which is better than from safe investments.

With this premise, the salesman should be fully aware of the effects upon the company of the prices he gets for the products. Since selling price is not determined by cost, there will be a considerable variation in returns from the individual products. The selling price will be determined by what the market can bear and although in some instances this may seem to be a very cutthroat way of going about things, the effect of competitive effort provides a driving force which eventually brings prices to a level which all can afford.

It does, however, make the salesman's task a very difficult one. If he underbids, his company loses. If he overbids, a competitor will get the job. In the end, by trial and error, the right price level is found and orders obtained.

The correct assessment of what the market will bear at any given time is difficult. The state of the particular industry: Is it highly competitive or is it in the early stages where price margins are high? What does the product do for the customer? What other methods are available to him? How urgently is the product needed?

All these are factors which must be weighed up in setting prices. The mixing of products is, therefore, aimed at providing the best possible sales. Just how this mix occupies all the machines is the problem of the production engineer. Whether or not all machines will be used or whether some will be overloaded will determine whether or not he will be able to meet the sales target and what his actual costs are likely to be.

The accountant should be able to provide figures which show just what action should be taken by the sales force to change the product mix in such a way that the production engineer can operate at maximum efficiency while, at the same time, obtaining the optimum added value for the labour force.

It should be possible to predict the changes required in production technique to meet alternatives in product mix and to show just where and how the introduction of new machinery would affect the trading position of the company as a whole.

PRINCIPLES OF ENGINEERING ECONOMICS

The advent of the computer has enabled a much more sophisticated approach to these problems, but not all production engineers and not all salesmen are familiar with the latest scientific techniques or how they can be used.

There is a simple approach which in a large number of cases could be applied to the problems of small firms and which would lead to an understanding of just what could be done at a later stage when the problems are bigger. A. W. Rucker in 1932 formulated the concept of added value.

The term denotes the change in value wrought upon the raw material by labour. This may be defined as: sales price less metal cost less cost of all other materials and services which are needed to manufacture the articles.

Sales price is known as well as metal cost and can be related to specific articles. The materials, on the other hand, may not be so easily to allocate. For example, chemicals used in processing, the amount of gas used in brazing, heat and light. These costs can be assessed only in total and then spread over the total number of parts produced to arrive at a unit cost.

Labour divides into two forms: those actually employed on producing parts and what is now called indirect labour but should really be termed support labour. These will be toolroom personnel, inspection, progress chasers and hourly paid supervisors. The money paid to this force, together with fringe benefits such as insurance, vacation pay and health services constitutes the labour cost. AV (added value) = sales price − metal cost − materials cost. LC (labour cost) = (direct labour cost + support labour cost) + fringe benefits.

The ratio AV/LC = production ratio is a useful guide as to the contribution made by an individual article or, when converted in total, to the over-all efficiency of the company.

It would be very useful for firms to know just what the general trend is in their country and what the value is for their industry. This would be of great help to both the salesman in assessing his firm's competitive position and to the production engineer in assessing whether his techniques were sufficiently effective.

To the other main items of expenditure, sales and administration (S and A), may be added research and development (R and D) and the money to be set aside to offset the deterioration in value of the machinery and equipment (D).

The trading surplus (TS) can then be written $TS = AV - LC - (S \text{ and } A) - (R \text{ and } D) - D$. The ratio of this trading surplus to the invested capital then determines the viability of the company.

For convenience, the accounting procedures are usually brought into action each month and sets of figures are produced to compare performance over previous intervals.

If the total estimated labour costs and added values for each product sold during this monthly period are plotted graphically, a pattern of points will emerge. This pattern delineates the product mix. A simple statistical assessment of the mean value will give a line shown as S in figure 15A. The slope of this line is the theoretical production ratio that could be obtained by the mix of products.

Those above the line constitute good products from the point of view of their contribution to the trading surplus; those below would require more labour than their total returns warrant. Product 1 is good, as well as product 3, but product 4 should not really have been accepted. The difference between the added value and that which would have been obtained for a job with the same labour cost but whose added value was at the intersection of the vertical for the labour cost and line S may be taken as the opportunity loss. If the sales force had clearly understood this then they would probably have not insisted that production take the job and would have attempted to mollify their customer by accepting only a small portion of the order.

At the month's end, the total added value and total labour costs can be assessed, taking into account that portion of labour which has been devoted to maintaining the work in process. The production ratio can be seen in the dotted line in figure 15 designated as *P*. This is lower than the sales estimate and its relationship to *S* is a measure of the efficiency of the production department.

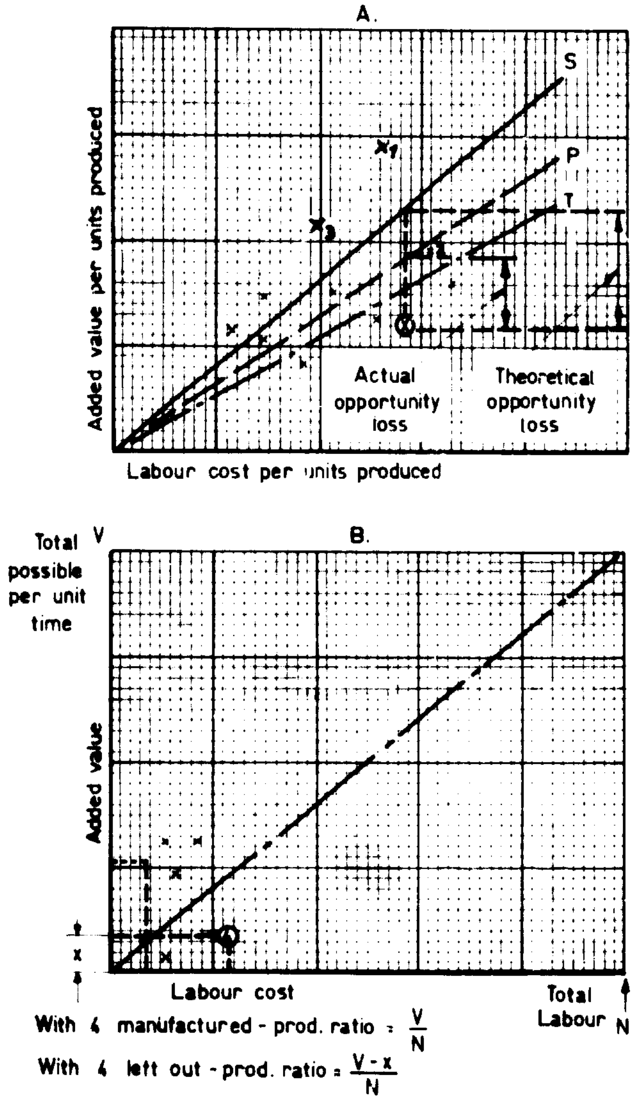

Figure 15

The graph can be extended to embrace the total labour cost which can be attained, that is, defining the total labour force and the total added value that can be obtained. When the labour force is virtually fixed, a small total added value even though theoretically favourable would result in a poor production ratio, *P*, and indicate the amount of surplus labour.

It is also possible by these methods to examine the manufacturing processes of individual products and determine whether or not the labour costs can be reduced. If these are as low as can be obtained with the equipment in operation, then the increase in price to make the continued manufacture worth while can be determined.

For given levels of labour cost and for different levels of efficiency of working it is possible to determine the level of trading surplus that can be attained as in figure 16. This assumes a constant level for *S* and *L*, *R* and *D*, and *D*. A company can then determine its minimum requirements in terms of trading surplus and this, in turn, for a given labour force, can be translated into line *T* on the graph in figure 15A.

The production engineers must ensure that line *P* is at a greater slope than line *T* and the sales force can determine what products to push and what to leave out in order to attain this.

If a given product is either lost to a competitor or left out as a matter of policy, the effect upon the trading surplus can be determined by reducing the total added value by the amount but retaining the total labour cost (since labour will not generally be reduced for small changes). This will give a production ratio which can be read across the corresponding net surplus as shown in figure 15B and figure 16.

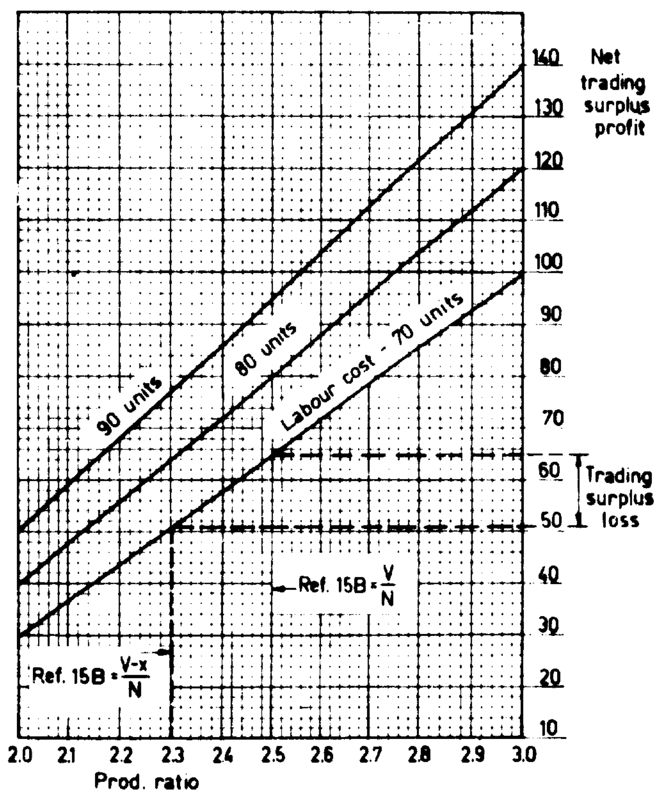

Figure 16

This simple approach does not take into account the effect of constraints in the production system. It may be that certain equipment constitutes a bottleneck. Again turning to figure 15A, the production of item 4 may occupy a certain piece of machinery which has also to be used for items 1 and 3. The net result of this might be that less of 1 and 3 can be produced if all of 4 has to be made. This would compound the ill effect of manufacturing item 4 as, if the amounts of 1 and 3 could be increased, the possible production ratio S would be much greater. Where there are a number of constraints affecting many of the items produced, then the problem becomes complex. In these circumstances a study, relating all the items to be produced, their production rates, costs and the constraints in terms of a matrix of linear equations, can be made for which a computer will provide answers similar to those derived in the simple way.

Projected estimates of product sales can be divided into product types and detailed requirements. From this can be derived optimum methods of manufacture and specifications of possible machinery for production. Theoretical assessments along these lines will enable determination of where the maximum returns can be obtained for a given capital investment. For example, in a factory manufacturing a number of items, a section dealing with grinding is overloaded in the manufacture of certain products which are in themselves very profitable and whose total volume is fairly large. A good case could be made out for more machinery to alleviate this problem. The toolroom, however, needs a similar grinding machine to deal with the increased load in servicing the tools for other machines needed to produce a much larger and equally profitable line of products. The returns from installing the grinding machine in the toolroom, by normal accounting assessment procedure very difficult to justify could, in fact, yield returns many times greater than from putting it in the production line.

In terms of replacement policy, it is therefore necessary to consider the system as a whole and plan the introduction of new or replacement machinery in a pattern which will fit the short-term as well as the long-term requirements.

In what has been called the conventional approach, the production engineer has (by reasons of his remoteness from the over-all picture) tended to think purely in terms of the increased efficiency of the individual units under his control. He isolates the returns to that particular section, with the real issues blanketed or fogged by the arbitrary assessment of overhead costs, materials often used being lumped together with fringe benefits and depreciation costs in such a way as to confuse the issue and prevent a true assessment of how he is using his labour.

By the suggested approach, much of this misunderstanding can be removed and the production engineer and the sales engineer can look quite dispassionately at the basic effects of their actions upon the company's trading position.

Cost of Replacement and New Machinery

The principle of setting money aside to allow for the dilapidation and general wear and tear of machinery is sound. However, the rates at which this has been set in the past have been purely arbitrary and unrelated either to obsolescence, from the point of view of production techniques, or to the true condition of the machinery. There has been an ingrained belief that one should conserve capital equipment and by doing so minimize costs.

Fortunately or unfortunately, the limiting factor in the past has been the cutting tool itself. The time lost in replacing a worn cutting tool has determined the optimum rate at which metal should be removed.

Consider the equation given for determining cutting conditions:

$$TMC = TR + \frac{CRT}{CO}\left(\frac{1}{a} - 1\right)$$

Where

TMC tool life for minimum cost
TR tool replacement time when worn
CRT cost of the tool cutting edge
CO overhead rate
a tool-life exponent in the metal-cutting equation $ST^a d^b f^c = G$
d depth of cut
f feed per revolution
G the machinability constant for the group of materials being considered
S surface cutting speed
T time for the tool to wear out or to reach a given condition of wear
c exponent for the feed factor

Where the overhead rate is high, the expression CRT/CO becomes small. Overhead in the equation is comparable to the total labour costs, that is, costs incurred by both direct labour and support labour plus contributions to sales and administration and depreciation. In big firms, this will be large and, as can be seen in the graph in figure 16, the larger the total labour cost the higher must be the production ratio for a given trading surplus to satisfy a given capital outlay.

In the small companies where the costs are low, the minimum cost is obtained by taking this low overhead into consideration and where a very expensive cutting tool has to be employed it would appear to pay better to conserve this by operating at lower speeds.

The fallacy in this argument is that the cost has no relationship with the selling price and that the added value of the article should determine the rate of production. It is obviously better to produce as fast as possible in order that time saved can be employed on other profitable work. The graphs in figure 17 illustrate this point.

From this it can be derived that in almost all cases it is probably the best policy to drive machinery to its maximum, bearing in mind that finishing operations and accuracy must not be impaired. The type of business will obviously determine the pattern of machinery to be used and the nature of the market it serves will also influence the decisions in what type of equipment would be needed. The jobbing shop will tend to try and remain as flexible in its array of operations as possible while the specialist product firm will in the future tend to employ more and more specialized machinery. The growth in sales of special machine tools over the past few years has been considerable. The automotive industry is a typical example but the trend has been set, particularly in the

United States where labour costs are high, to move away from standard machine tools to highly specialized, fully automated installations. Market growth has been sufficient to warrant such an approach. Even in these cases the emphasis will be in driving the machinery to the limit to take the best advantage of the market situation and over the period of the project to obtain the best possible returns. Much research is now being carried out in the problems of machine-tool wear and incorporation of such developments as hydrostatic bearings will probably be standard in all high-production machine tools in the future.

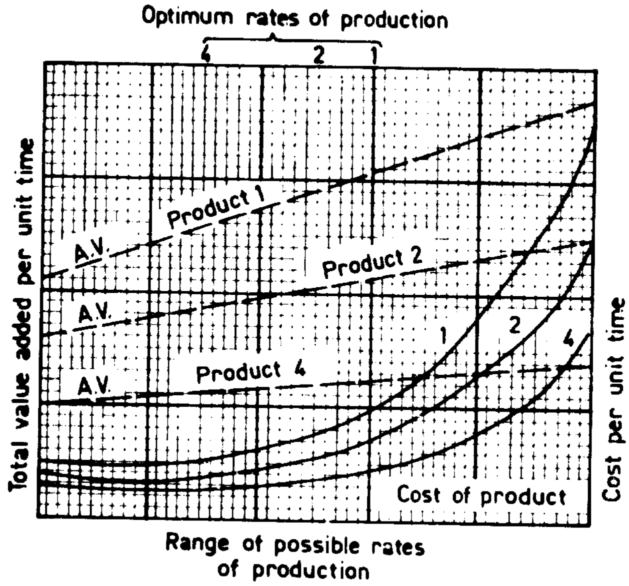

Figure 17

The productive time saved by the use of fully automated devices such as tape control with feed-back controls from the cutting operation will help to offset the high capital cost of some of these innovations, but additional expenditure may be necessary to make these complicated electrical, hydraulic and air systems more reliable. Down time will need to be at a minimum for servicing and the correction of faults if such sophisticated machinery is to be introduced. The cybernetic principle of redundancy must be applied wherever possible. This principle involves the superimposition of a number of control circuits, each in parallel and capable of performing the operation. If one fails, the others take over. In this way, the circuit system is no longer dependent upon the reliability of the individual components and its reliability as a whole increases many thousands of times. The cost of the extra circuits will be very small compared to costs if the machine breaks down.

There is a limit to the amount of capital that can be employed effectively to exploit a given market situation.

If we consider the equation $TS = AV - LC - SA - D$ where as previously given TS = trading surplus; AV = added value; LC = the total labour costs, both direct and support; SA = sales and administrative expenses; and D = the depreciation figure, then we can see that for a given market where the added value is more or less fixed, LC and D determine the value for TS.

There is a limit to which the value of LC can be reduced, as this involves both those actually operating machines and those who keep them running, both the equipment and refurnishing the cutting tools, i.e., electronics experts and toolroom personnel. The cost of the support labour will rise with increased automation since a high degree of specialized training will be needed to ensure satisfactory performance by these people.

If we consider a certain product and the effect of mechanizing or automating the operations, one can express this in graph form, as in figure 18. The degree of assistance to the actual labour forms the base and the cost of direct labour; support together with the cost related to the capital expenpiture (as on predetermined rate of return) forms the vertical axis.

The summation of these factors yields an optimum expenditure and determines the degree of mechanization or automation that should be employed.

It is possible to express the same situation in another way and relate the expenditure to the improvement in the production ratio. In figure 19, it can be seen that when the cost of automation rises rapidly, surplus will fall off indicating that in each case there will be a point beyond which it is not worth pursuing full automation. The cost of automation is seen as a depreciation or capital recovery charge and this is obviously related directly

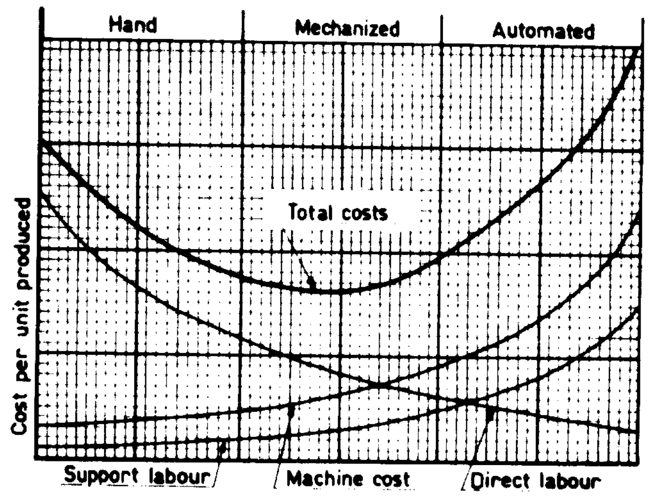

Figure 18

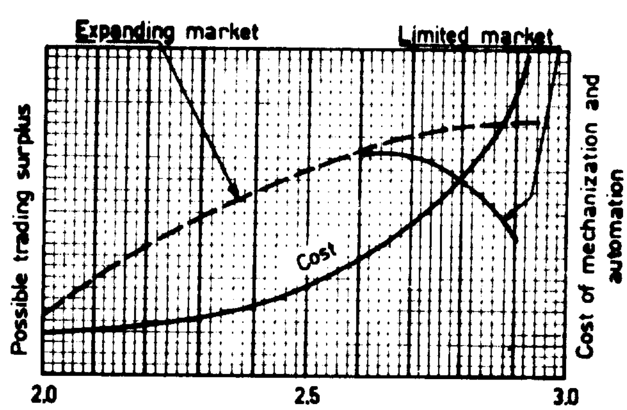

Figure 19

to volume produced. The greater the volume the less will be the value of D in the equations and the further to the right will be the trading surplus optimum in figure 19.

With the move to more and more specialized machinery, it can be seen that the longevity of the production equip- must be related more and more to the duration of the project. It will have to last and perform satisfactorily until a new product in concept of manufacture renders it obsolete. With standard machinery working in conjunction with specialized equipment, the same rules will apply and the tendency will be for such to be designed to give the maximum output over shorter durations of time.

Budgeting for capital expenditure

From the foregoing, it can be seen that even in small firms it will no longer be wise to budget for capital expenditure by purely off-the-cuff guesses. Quantified relationship between the sales projections, with their attendant market constraints, can be made with the degree of production expenditure and with its calculated effect upon the efficiency of the organization as a whole. The mathematical equations for the various relationships can be obtained and by a process of iteration the optimum expenditure commensurate with returns calculated. The services provided by the computer are now well within the reach of all sizes of firms, either by renting time or by actual purchase. These equations when formulated constitute what is termed "soft ware" as opposed to the physical entity of the actual computer installation categorized as "hard ware".

The group of equations as soft ware constitute a mathematical model of the organization upon which experiments can be tried out. These experiments would take the form of considering various possible market situations and then determining the optimum degree of capital expenditure. That is, how much mechanization or automation would produce just how much trading surplus. By making the model more complex and relating the operations of the various departments within the firm, the interactions of restraints or production bottlenecks can be assessed and the returns in terms of the organization's trading calculated.

In this way, many of the possible future developments in terms of market changes and the attendant effects upon the company can be analysed and from these a policy laid down which will be as near the optimum as possible.

Summary and conclusion

An assessment is given of the effect of rough-and-ready policies on ultimate factory efficiency when considering the replacement of standard machine tools by tools of a similar technological standing. In the light of this the effect of merely replacing the tool or introducing new or better techniques can be determined, but in all these approaches the link between the machine tools, the constraints that each group of machines places upon the other in relation to the factory output as a whole, is missing.

A simple approach to engineering economics enables an understanding of the sophisticated methods that are now available.

By studying the interaction of all the machine tools and processes and constructing a model which relates their operations mathematically, either by techniques such as linear programming or simulation, to their outside or sales environment, their requirements can be matched to predicted future requirements. The company may decide to diversify its operations or embrace new markets with products not previously manufactured. It may introduce new technologies in a field it already exploited or increase the production of the goods it already makes.

In all this, a forward prediction or marketing plan is the first requirement and this must be matched to the model of the company in its present form. The deficiencies in production capabilities can be determined for optimal profitability. These specifications may, in the first instance, be impracticable, but they may indicate profitable lines of development. The type of machine tool which can be made will have a performance which can again be assessed as to what its effect will be on the factory as a whole. This may be shown to exceed by many orders of magnitude the returns related to its individual productivity.

The capital outlay needed to finance these new tools can be assessed in terms of the productivity of the factory and a much more accurate calculation made of the ultimate returns. It is now possible to hand large investments covering many factories and business in a large corporate body, timing the introduction of new equipment and installations to maximum profitability. It is interesting to note that the conclusions from such a study indicate that the solutions are robust from the point of view of the actual expenditures, even though the markets may not develop precisely as predicted. All that happens is that the timing of the capital expenditures may either be delayed or advanced to meet the situation.

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