A comparative method of analysis for evaluating sheet metal machine tool flexibility

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Abstract
In the machine tool sector, for production purposes, flexibility and automation are elements that play conflicting roles because greater automation generally means less flexible production. As a result, it is not easy to choose between technologies that have different degrees of automation or may even be manual. We are therefore proposing a comparative method of analysis that can be used to evaluate one machine tool with respect to another, which is used as a reference. This combination leads to the identification of breakeven points on productivity, flexibility and automation that, when taken together, provide criteria for evaluating the economic suitability or unsuitability of the choice in hand. This comparative model rotates around evaluation variables that have long been consolidated and recognized by sheet metal machine tool manufacturers and users.

Introduction
Machine tool flexibility, mainly in the specific context of sheet metal manufacturing, is the subject of much discussion. Customers’ needs have, by now, been consolidated against manufacturers’ products around a number of well-defined numeric variables. Other, less well-defined, factors also come into play, making rational evaluation even more difficult. The purpose of this analysis is to establish a rational connection, in the form of a behavioural model, between the numeric variables that are generally recognized, by both customers and suppliers, to be the elements for objective evaluation.

Customers express their needs in the form of production volume and mix. Suppliers respond with on-line set-up and cycle times, completing their proposals with selling prices and, perhaps, details of machine efficiency. Volume is understood to be the number of parts to be produced in the medium-long term, whereas mix is reduced to identifying the average production batch from the family of parts that can be made on a given machine tool. The model of analysis rotates around these elements of evaluation in order to provide comparative breakeven points on the productivity, flexibility and degree of automation of the machine to be purchased. It will therefore identify criteria for the number of machines to be taken into account, the size of the critical batch and the amount of labour used.

Literature on this subject is wide-ranging but does not, in our opinion, manage to formalize in economic/productive terms what machine suppliers provide and what manufacturers of sheet metal articles require. Grubbstrom/Olhager [1] analyze the mutual relationship between the productivity and flexibility of a generic production system in order to define dynamic flexibility as the maximum speed at which a transformation can take place between two points in a production space erected on important input and output variables. Their analysis is rather formal and generic, whereas the work
we shall describe is based on comparative criteria between two specific machines. In a very general
form, Dobsons/Karmakar/Rummel [2] study the influence of the setup time between different
machines in order to optimize the subdivision of their workloads. In a previous work, the same
authors [3] analyse the subject in terms of the best batch sequence that can be planned for a single
machine. In both cases, the approach is based on known production variables, whereas in our case
we are interested in the selection criteria for the purchase of a machine, which is based on generic
mean variables. The critical nature of setup time and batch size is also analyzed by Karmakar [4] in
a different context (MRP), that of optimizing lead times and in-process inventories.

The basic model of analysis

If we define \( A \) as the average time taken for the set-up of the machine between one batch and the
next, and \( a \) as the average time taken to produce one part, the time \( t \) required to produce \( N \) parts
sub-divided into batches with an average size of \( n \) will be:

\[
t = Af\left( \frac{N}{n} \right) + aN ,
\]

where \( f \) is the cut-off function to the next integer for the rational number \( N/n \). This function is not
always derivable because of the sharp corners introduced by \( f(N/n) \): Fig. 1 shows its trend clearly.
If \( N \) is large enough, as in the model we are proposing, we can approximate each integer \( f(N/n) \) with
the corresponding real number \( N/n \). The resulting function will be continuous and derivable
throughout its domain of definition and will have the following form:

\[
t = \left( \frac{A}{n} + a \right) \frac{N}{k\alpha} ,
\]

where the analysis variables \( k \) and \( \alpha \) have been added to take account of machine price/cost and
performance respectively. All these variables, including \( n \), can easily be considered as belonging to
the continuous domain of positive real numbers, even if they sometimes express natural quantities.
The variable \( \alpha \), which is greater than 0 and less than 1, represents machine efficiency, or
performance, and is used to take account of stoppages for breakdowns or preventative maintenance.
In view of the definition of \( k \), we can hypothesize assigning values of 2, 3, 4 … to \( k \) to represent
reductions in the production time \( t \) to one half, one third and so on, thanks to investments that allow two or
more identical machines to be put in parallel. Following this criteria, if we spend more money to
purchase/run a machine, we must expect a corresponding reduction in the production time \( t \). As a
result, \( k \) will have positive real values to represent either a price/cost variation or a machine parallelism
factor. We can thus define a principle of conservation of the price-cost/performance ratio:

*If a machine produces double the quantity of a particular item in a given time
than a reference machine, we will be willing to shoulder up to double the price-
cost.*
This principle is considered to be valid in the sheet metal manufacturing field because the machines used are all pretty flexible and the manufacturing processes are not complex, with the result that the criteria of economy of scale are not generally used. That said, we can now start with the total differential of function (2)

\[
dt = \frac{\partial t}{\partial A} \, dA + \frac{\partial t}{\partial a} \, da + \frac{\partial t}{\partial n} \, dn + \frac{\partial t}{\partial \alpha} \, d\alpha + \frac{\partial t}{\partial k} \, dk ,
\]

and, after a number of steps, we can obtain the relative variations - or percentages - for each of the variables under discussion. The result in the form of the relative variation of the variables under discussion is:

\[
\frac{\Delta t}{t} = \frac{A}{A+na} \left( \frac{\Delta A}{A} \cdot \frac{\Delta n}{n} \right) + \frac{na}{A+na} \frac{\Delta a}{a} - \frac{\Delta \alpha}{\alpha} - \frac{\Delta k}{k}
\]

which shows, in analytical terms, something that is generally perceived by operators in the sheet metal manufacturing field, but is almost always formulated only in qualitative terms. In fact, the first term \(A/(A+na)\) represents the contribution of the setup time which tends towards zero when \(n\) is very large. The second term \(na/(A+na)\) is the weight of the cycle time which tends towards 1 when \(n\) is very large. The sum of the two terms is constant and equals 1, showing that the role of the two terms, as the \(n\) dimension of the batch changes, is complementary; low values of \(n\) therefore assumes a hyperbolic weight in our analysis.

**Productivity and machine parallelism breakeven point**

The hyperbolic weight of the average batch size \(n\) on productivity pushes the analysis in this direction, especially when comparing technologies that appear to offer the same service. For this purpose, let us imagine two hypothetical machines, \(A\) and \(B\), with an average on-line set-up time of \(A\) and \(B\), an average cycle time of \(a\) and \(b\) and performance of \(\alpha\) and \(\beta\) respectively. Lastly, let us define \(k\) as the relationship between the purchase prices and running costs of the two machines, as follows:

\[
k = \frac{priceB + y \cdot serviceB}{priceA + y \cdot serviceA} ,
\]

when it is machine \(A\) that has the poorer performance. In this equation, "price" is the purchase price, "service" is the annual running cost and \(y\) are the number of years for which the machine is expected to be used, i.e. the expected machine lifetime and not the pay-back period. In theory, \(k\) should always be greater than 1, but it is a well-known fact that prices and costs do not always follow analytical logic. We can therefore rewrite equation (2) for the two machines we are evaluating as well as for a third imaginary machine \(K\), representing the revaluation of the reference machine \(A\) in accordance with a direct price/cost relationship.
If we take \( N \) as an independent variable and keep all the other variables constant, we will obtain the straight lines shown in Fig. 2 where \( t_A > t_B \) shows that the first machine is less productive than the second. By direct comparison between functions (6) and (7), we can write the condition

\[
(A + na)\beta > (B + nb)\alpha ,
\]

in order to identify \( A \) as the machine with the poorer performance. If the inequality is not satisfied, \( B \) will be the machine with the poorer performance: this consideration serves only to give the machine with the poorer performance the role of reference machine for the sake of comparison; this is done merely to facilitate our analysis and does not have any effect on the present discussion.

Imposing a condition of parallelism between the two straight lines \( B \) and \( K \) we obtain

\[
z = \frac{(A + na)\beta}{(B + nb)\alpha} ,
\]

where the symbol \( z \) is used instead of \( k \) to prevent ambiguity with definition (5).

The \( z \) function (10) represents the machine “productive parallelism” factor, meaning that the poorer performance of machine \( A \), which is implicit in \( K \), can be covered by purchasing \( z \) type \( A \) machines and making them work in parallel. It is therefore important not to confuse \( k \) with \( z \): the former is imposed by the surrounding environment whereas the latter is the result of the solution of the system in the two equations (7) and (8) with respect to the unknown variable \( k \). In other words, \( k \) reflects commercial and environmental policies whereas \( z \) is the result of technical specifications. If the following amount:

\[
S = (z - k) \cdot (price_A + y \cdot service_A)
\]

is positive, it represents the monetary value – or profit – that is obtained by using the machine with the better performance \( B \) to make exactly the same things as the virtual machine \( K \), which is the image of the reference machine \( A \). If the amount is negative, machine \( B \) is overvalued, because its use for \( y \) years generates an economic loss \( S \). Overvaluations must be linked to quality and
environmental benefits recognized by both parties because, analytically speaking, they cannot be justified. Function (11) is the result of adopting the aforementioned principle of conservation of the price-cost/performance ratio. $=0$ is the machine parallelism production breakeven point for a given machine lifetime $y$. The parallelism is virtual because $z$ and $k$ are real numbers and not integers.

**Flexibility and batch breakeven point**

Functions (6) and (7), analyzed with $n$ as an independent variable, represent hyperbolas with a common point that is identified by the solution of the associated system of two equations. To the analytical solution, which we shall conventionally call $n'$, we can add the physical condition of being greater than or equal to 1 because it identifies the dimension of a batch of parts. We will obtain:

\[ n' = \frac{A\beta - B\alpha}{b\alpha - a\beta} \geq 1 \]  

(12)

If this condition is satisfied, it identifies what we shall call the “productive batch breakeven point” because it identifies an average batch value $n'$, below which flexibility is privileged but above which rigidity prevails, with a term of comparison on $t$ or productivity (see Fig. 3).

![Fig. 3 - Flexibility $t=f(n)$. Production and economic batch breakeven points](image1)

![Fig. 4 - Price-performance $S=f(n)$ with production and economic batch breakeven points](image2)

It goes without saying that in this context we are talking about production flexibility which increases as the dimension of the production batch decreases. If the solution of the system of equations $A$ and $B$ does not satisfy condition (12), the hyperbolas will not have any common points in the interval between 1 and $\infty$ to show that a comparison is being made between machines with different levels of performance but the same degree of flexibility. If we repeat all the above considerations for functions (7) and (8) too, comparing machine $B$ with the virtual machine $K$, we will obtain a second condition as follows:

\[ n'' = \frac{A\beta - kBa\alpha}{kb\alpha - a\beta} \geq 1 \]  

(13)
The value \( n \) that we have thus identified (Fig. 3) represents the “economic batch breakeven point” in the sense that machine \( B \) being analysed can be economically undervalued or overvalued according to the principle of conservation of the price-cost/performance ratio we applied when constructing equation (11). This is confirmed by the fact that, if we impose the condition \( S(n) = 0 \) in equation (11), we will obtain the same result as that expressed in equation (13). Fig. 4 shows the graph for equation (11), analyzed in terms of \( n \), for comparison with Fig. 3. The following equations help to show the above price/performance function \( S(n) \) trend. In the interval between 1 and \( \infty \), this can assume either the downward trend shown or the opposite upward trend, depending on which machine is chosen as the \( A \) reference machine.

\[
\lim_{n \to \infty} S(n) = \left( \frac{a\beta}{b\alpha} - k \right) (priceA + y \cdot serviceA) \quad (14)
\]

\[
S(0) = \left( \frac{A\beta}{B\alpha} - k \right) (priceA + y \cdot serviceA) \quad (15)
\]

\[
S(n) = \pm\infty \text{ per } n = -B/b \quad (16)
\]

**Automation and labour/services breakeven point**

In the sheet metal processing sector, a particular finished part can very often be produced both on completely manual machines and on machines with different degrees of automation. The choice between simple machines and manpower at one extreme and more sophisticated machines and specialized manpower at the other is an open and much-debated question. If we exclude manual machines, which nevertheless still have their uses, many manufacturers today employ highly automated machine tools for forming and these improvements require an increasing amount of effort. Attention is therefore moving from automation to the disturbance generated in the production process by the presence of the machine itself: the higher the level of automation achieved, the greater the disturbance will be. Sources of disturbance include moving and tracking raw and semi-finished parts, off-line tool setup, off-line programming, staff training and so on. To take account of this, we can use the considerations we have already made: in fact, both the labour for a completely manual system and the amount of service required from specialized staff to program and set up machines with different degrees of automation can be added, as an annual cost, to both equations (5) and (11) which contain the variable "service". With these considerations, if we take equation (11) and impose the condition of cancelling the amount \( S \), the value will become zero for \( k = z \) which, by virtue of (5), will give us the following equation:

\[
\frac{priceB + y \cdot serviceB}{priceA + y \cdot serviceA} = z .
\]

If we attempt to find \( y \), we will obtain a new number of years:
\[ y' = \frac{z \cdot \text{price}A - \text{price}B}{\text{service}B - z \cdot \text{service}A} \]  

(18)

which represents the labour/services breakeven point, i.e. the number of years needed to cancel the over/undervaluations (\(S\)). The number of years \(y'\) in equation (18) should always be less than the number of years \(y\) for which the machine is expected to be used, as defined in equation (5). If this is not true, the over/undervaluations \(S\) in equation (11) cannot be recovered and will assume a quality/environmental value. For example, in Fig. 5, the point of intersection between the straight line \(V = \text{price} + t \cdot \text{service}\) for machine \(B\) and that for an equivalent machine \(zA\), can have an abscissa that is either negative or much greater than the life expectancy of the machine: in the first case, the machine being analysed \(B\) will be more remunerative than the reference machine \(A\) from the very first day of operation, whereas in the second case the undervaluation will never be recovered.

**Example of batch breakeven point**

We shall now apply the model we have developed in order to compare two machines with different degrees of automation: a punching-bench machine \(A\) and a high-speed punching machine \(B\). The first machine privileges the production cycle with respect to the partly manual set-up phase; the second, on the other hand, is fast during the totally automatic set-up phase but slower in the production cycle. In this case, a productive batch breakeven point \((n')\) can be identified because condition (12) is generally satisfied. This type of comparison is very sensitive to changes in batch size \((n)\) but less affected by being used on more than one shift. With typical data from a specific case of application in the sheet metal forming sector, we can hypothesize:

\[ A = 30 \text{ minutes}, \quad B = 5 \text{ minutes}, \]
\[ a = 20 \text{ seconds}, \quad b = 40 \text{ seconds}, \]
\[ \alpha = 98\%, \quad \beta = 98\%. \]

300 and 600 kiloEuro are the purchase prices of machines \(A\) and \(B\) respectively. Annual running costs (energy, service technicians, maintenance and spare parts) are respectively 35 and 30 kiloEuro for work on a single shift. The less automated punching bench \(A\) has a greater cost because of the service labour needed to set it up. Both require the same amount of technical service for CAD-CAM programming. The period of use \((y)\) is 10 years and the average batch size \((n)\) can be assumed to be 100 parts. The formulae give the following results:

\[ k = 1.38, \quad z = 0.88, \]
\[ n' = 75 \text{ parts}, \quad n'' = 39 \text{ parts}, \]
\[ y' = 360 \text{ years}, \quad S = -326 \text{ kiloEuro}. \]

The more highly automated high speed punching machine \(B\) produces less than punching bench machine \(A\) with a ratio of 1/0.88 whereas the cost ratio is 1/1.38. According to the principle of maintaining the price-cost/performance ratio, machine \(B\) is overvalued by 326 kiloEuro. In fact, if machine \(B\) were to cost 600-326=274 kiloEuro, the variables would balance out with \(S = 0\) and \(y' = y = 10\) years: the principle would be respected but the result would not be acceptable to the supplier of the technology for machine \(B\). Even according to the alternative principle of productive parallelism, which compares \(B\) with 0.88 \(A\) machines, the result would not be acceptable because the cost breakeven point \(y'\) would be 360 years. The high speed punching machine \(B\) is not suitable for this type of work. If we reduce the average batch size to 75 parts, we will obtain:
In this condition, the productivity of the two solutions is identical \( z = 1 \) and \( B \) is overvalued by 250 kiloEuro; economic parity is reached in 60 years and solution \( B \) is not acceptable unless the purchase price is reduced by the same amount.

With this data, the machine becomes worthwhile if production batches are relatively small (i.e. less than 39 parts); in fact, with \( n = 30 \) we will obtain:

\[
\begin{align*}
    k &= 1.38, \\
    z &= 1.60, \\
    n' &= 75 \	ext{ parts}, \\
    n^* &= 39 \	ext{ parts}, \\
    y' &= 4.6 \text{ years}, \\
    $ &= +140 \text{ kiloEuro}.
\end{align*}
\]

Now, it is finally evident that the high-speed punching machine \( B \) is worthwhile if the economic context is as we have just described: in fact, machine \( B \) will produce as much as \( 1.6 \ A \) punching-bench machines and will reach cost parity before the hypothetical life of 10 years. 140 kiloEuro can be saved by using high speed punching machine \( B \) instead of \( 1.6 \ A \) punching bench machines to produce the same volume of parts. \((300+35*10)*1.6-(600+30*10)=140\).

**Example of labour/services breakeven point**

Continuing with the model we have developed, we shall now compare a manual machine \( A \) with an automatic one \( B \) which has much shorter set-up and production cycle times. Machine \( A \) is a common manual press-brake while machine \( B \) is a special forming machine called a Panel Bender. In this case, there is not usually a productive batch breakeven point because the machines have a comparable degree of flexibility. This type of comparison is therefore not particularly sensitive to batch size \( n \) but use on more than one shift generally leads to the totally automatic machine being chosen because it requires less labour. With typical data from a specific case of application in the sheet metal forming sector, we can hypothesize:

\[
\begin{align*}
    A &= 20 \text{ minutes}, & B &= 10 \text{ minutes}, \\
    a &= 80 \text{ seconds}, & b &= 45 \text{ seconds}, \\
    \alpha &= 95\%, & \beta &= 98\%.
\end{align*}
\]

Efficiency \( \alpha \) is lower than \( \beta \) because it is assumed that the operator of the manual press-brake \( A \) will not be able to maintain a constant rate of production. 60 and 600 kiloEuro are the purchase prices of machines \( A \) and \( B \) respectively. Annual running costs (energy, labour, maintenance and spare parts) are respectively 79 and 55 kiloEuro for work on two shifts. The manual press-brake \( A \) has higher costs because of the labour required, whereas the automatic machine \( B \) requires more energy, maintenance and spare parts. The period of use \( y \) for both machines is assumed to be 10 years and the average batch size \( n \) is assumed to be 150 parts. The formulae give the following results:
We can say that the Panel Bender $B$ produces as much as 1.85 manual press-brakes $A$ with a cost ratio of 1.35. According to the principle of maintaining the price-cost/performance ratio, machine $B$ is overvalued by 425 kiloEuro. In fact, if machine $B$ were to cost 600+425=1025 kiloEuro, the variables would balance out with $S=0$ and $y'=y=10$ years: the principle would be respected but the result would not be acceptable from the production point of view because of the wide gap in prices and performance. This is where the alternative principle of productive parallelism becomes useful: it compares machine $B$ with 1.85 $A$ machines and gives a breakeven point ($y'$) of 5.4 years, which is less than the machine life expectancy $y$ of 10 years. The automated machine $B$ is shown to be worthwhile. 

If we halve the running costs by assuming that the machine will work on a single shift, because labour, energy and maintenance are linear functions over time, we will obtain:

$k=1.92$, $z=1.85$, $n'<1$ undefined, $n''=21$ parts, $y'=10.7$ years, $S=-32$ kiloEuro

**Conclusions**

The model we have proposed is suitable for machines that do not produce multiple or nested parts. Care must, therefore, be taken when using it in such cases. It does, in fact, need to be developed further in this specific direction. The results obtained using this model must be interpreted with great care, because undefined factors of quality and social convention are also taken into account when making a choice. As in variational equation (4), the spirit of this document is to lay down a reference basis that can be used to evaluate the suitability of a machine.
References


