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MANUFACTURING FLEXIBILITY:
MEASURE AND RELATIONSHIPS

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ABSTRACT

The study and formulation of manufacturing flexibility measures has been inhibited by a lack of a conceptual structure to encourage model development. In this paper, we introduce a framework to facilitate the development of flexibility measures. Existing measures for five flexibility types are tested using the framework and the 'best' measures from the literature are presented. For volume and expansion flexibility, the framework is used to develop new measures. This is followed by a discussion of the relationships between flexibility types and some sample relationships are highlighted.

1. INTRODUCTION

Flexible Manufacturing Systems (FMS) are technologies combining the benefits of both computers and numerical control machine tools. They are also technologies that have been hailed as the solution to the problems of manufacturing industries world-wide. However, soon after the rapid growth in FMS installations, operations managers realized that no simple solutions were available, and that flexible manufacturing systems would not easily answer the market's desire for more rapid delivery, more product variety, more customized product designs and higher product design turnover as evidenced by reduced product life cycle lengths. It is generally acknowledged that these market demands are driven by the advent of these technologies. Several companies have illustrated how successful use of FMS has resulted in the above-mentioned benefits to customers. These companies have realized that a successful technical implementation alone is not enough and that FMS investment must correlate with the corporate and manufacturing strategy the firm is following. When both business and technical success is achieved, the celebrated flexibility benefits may ensue, as recognized by Voss (1988). However, there is ample evidence (see Jaikumar 1986) to suggest that the management of such systems is no easy task.

Bolwijn and Kumpe (1990) and De Meyer, Nakane and Ferdows (1989) have identified 'flexibility' as the focus of the next competitive battle. De Meyer et al. state that this battle "will be waged over manufacturers' competence to overcome the age old trade-off between efficiency and flexibility". However, confusion over what constitutes flexibility still occurs. Gerwin (1993) suggests that the lack of full understanding of manufacturing flexibility is inhibiting progress towards the utilization of flexibility concepts in industry and impeding manufacturing managers from evaluating and changing the flexibility of their operations. Gunasekaran et al. (1993) and Gerwin (1993) identify the measurement of flexibility and performance as an important hurdle to achieving a full comprehension of FMS behavior, and a stepping stone to establishing full economic-based measures. Gunasekaran et al. (1993) also state that the complex inter-relationships between various aspects of flexibility will be further advanced by the

development of flexibility measures and that flexibility trade-offs "can help the management to support the manufacturing strategy of the firm".

2. MANUFACTURING FLEXIBILITY

The taxonomy of flexibility types established by Browne et al. (1984) has formed the foundation of most subsequent research into manufacturing flexibility. In an excellent review, Sethi and Sethi (1990) identified over fifty terms for various flexibility types, although generally the basis of all work has been that of Browne et al. For completeness we restate the Browne et al. definitions below.

Machine flexibility: "refers to the various types of operations that the machine can perform without requiring prohibitive effort in switching from one operation to another" (Sethi and Sethi 1990).

Process flexibility: is the ability to change between the production of different products with minimal delay.

Product flexibility: is the ability to change the mix of products in current production, also known as mix-change flexibility (see Carter 1986).

Routing flexibility: is the ability to vary the path a part may take through the manufacturing system.

Volume flexibility: is the ability to operate profitably at different production volumes.

Expansion flexibility: is the ability to expand the capacity of the system as needed, easily and modularly.

Operation flexibility: is the ability to interchange the sequence of manufacturing operations for a given part.

Production flexibility: is the universe of part types that the manufacturing system is able to make. This flexibility type requires the attainment of the previous seven flexibility types.

Measures for most of these flexibility types have been attempted. However, there

has not been a consistent structured approach to the measure development and, therefore, the success of these measures has been sporadic. Gupta and Goyal (1989) presented a classification of flexibility measures "based on the ways researchers have defined flexibility and the approaches used in measuring it". The categories defined are:

1. Measures based on economic consequences

2. Measures based on performance criteria

3. The multi-dimensional approach

4. The Petri-nets approach

5. The information theoretic approach

6. The decision theoretic approach

The measures created and evaluated in this paper are based on performance criteria, although the multi-dimensional approach is examined also.

2.1 Developmental framework model

The framework suggested is illustrated in Figure 1. The basis of the framework is straightforward: we believe the lack of consistency in existing flexibility measures is due directly to the lack of discussion of the purposes of such measures. Most of the literature purely lists proposed measures but rarely mentions the purposes and criteria against which the measure can be judged, qualitatively or quantitatively. This paper seeks to establish a clearly defined list of the uses for the measure of a flexibility type and a list of criteria against which a proposed measure may be judged. In some cases the measure itself is defined, keeping in mind the purpose of the flexibility type and how the measure may be used. The purposes of the flexibility measure will be largely determined by the flexibility measure category, defined in Gupta and Goyal (1989).

<Insert Figure 1>

The framework will be used as a validation tool. Flexibility measures for various flexibility types are assessed relative to a list of criteria generated after the purposes of the flexibility type and flexibility measure are examined. Accordingly, a "winner" is found for each flexibility type; the winners are judged to be those measures which comply with the greatest number of criteria.

2.2 Evaluations of existing measures

Using the framework described above we examined the literature with the intention of analyzing the existing measures, comparing the measures with purposes and criteria established separately. We found acceptable measures for five of the eight Browne et al. flexibility types and decided that further development of measures for these types would not be constructive.

Machine flexibility

Machine flexibility is the ability to perform a variety of operations on a single machine. The purposes of the measures are generally to capture characteristics of machine flexibility not portrayed by other equipment descriptors such as price, size, speeds, tolerances, weight and part limits. Some criteria for machine flexibility performance measures include: they must describe the main features, that is, the ability to change between operations with minimal setups and delays; they must be amenable to calculation; this would mean that they can be computed on a PC spreadsheet at most, and preferably on a calculator; they do not necessarily need be related to dollar terms given that performance measures are being looked at; they should "increase (decrease) in value if the machine can do more (fewer) tasks with positive efficiency" (Brill and Mandelbaum 1990); they should "increase (decrease) in value if the efficiency for doing any one task increases (decreases)" (Brill and Mandelbaum 1990); they should "increase (decrease) in value if the importance weight of any doable task increases (decreases)" Brill and Mandelbaum 1990); and they should "be applicable to continuous as well as discrete and multi-dimensional background sets of possible tasks" Brill and Mandelbaum 1990). Brill and Mandelbaum (1989, 1990) defined a measure for machine flexibility

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which tends to satisfy the purposes and criteria. The measure is simply a weighted normalized sum of task efficiencies. Task efficiency (some papers refer to it as effectiveness) is a measure of how well the machine can perform the relevant task. These efficiencies are weighted by how important the task is to the production of the part or product, whether the importance could be determined by time or economic factors. The only criticism that could be levelled at the measure is that it could be argued that the allocation of a continuous variable to the task efficiency is inappropriate. It might be said that a discrete 0-1 variable could better capture how efficiently a task has been carried out. We believe the efficiencies or effectiveness scale of tasks is not entirely realistic since it attributes a number between 0 and 1, whereas we suggest that in many cases it should be either 0 or 1, since a task only partially completed by the machine, may often be considered not done and therefore its effectiveness is zero. For example, a task requiring the drilling of a hole of depth 10 cm should not be allocated a task efficiency of 0.8 when a hole of 8 cm depth is drilled. A more appropriate task efficiency for this case is 0.

Process flexibility

Process flexibility is the ability to change between the production of different products with minimal delay. Browne et al. (1984) say it is "the ability to produce a given set of given part types, each possibly using different materials in several ways". Sethi and Sethi (1990) set out the purposes of process flexibility, namely to reduce batch sizes and reduce inventory costs. Other contributors suggest it can minimize the need for duplicate or redundant machines (Carter 1986), and protect against market variability (Carter 1986) by accommodating shifts in the product mix demand by the market. The criteria of a measure include: describe the main features of process flexibility, namely the ability to change between the manufacture of different products without prohibitive changeover time or cost; be amenable to calculation; increase (decrease) with increasing (decreasing) product portfolio size; increase (decrease) with an increasingly (decreasingly) versatile material handling system and increasingly (decreasingly) adaptive jigs; and increase (decrease) with decreasing (increasing) changeover cost and decreasing

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(increasing) changeover time. de Groote (1992) developed a pair of measures which capture the criteria quite well but concludes that the nature of the flexibility type prohibits the creation of a single measure.

Product flexibility

Product flexibility is, as defined by Browne et al. (1984), the "ability to changeover to produce a new (set of) products(s) very economically and quickly". Essentially this means the ability to change the mix of products in current production, and indeed Carter (1986) refers to this as mix-change flexibility. Sethi and Sethi (1990) rightly state that product flexibility is distinguished from process flexibility on the basis that addition of new parts will "invariably involve some setup". The purposes of a measure of product flexibility would be to act as a descriptor of this aspect of manufacturing flexibility. Possible usages of a product flexibility measure could occur in a manufacturer's strategic planning in positioning himself with respect to his products. The criteria of a measure include: capture the dominant dimensions of comparison; be applicable to various manufacturing technologies; increase (decrease) with the increasing (decreasing) number of parts introduced per time period; increase (decrease) with an increasing (decreasing) size of the universe of parts able to be produced without major setup; increase (decrease) with increasing (decreasing) scope of the limits of CAD, CAM and CAPP systems; increase (decrease) with the increasing (decreasing) level of system integration of the developmental tools; increase (decrease) with decreasing (increasing) time of design implementation through the system; increase (decrease) with decreasing (increasing) setup time when introducing a new product to the current production portfolio; and increase (decrease) with decreasing (increasing) setup cost when introducing a new product to the current production portfolio. Kochikar and Narendran (1992) propose an introducibility measure which relates to how well a particular product can be made by the system and, therefore, how the system can make a new set of products. Only some of the above criteria were met by Kochikar and Narendran's measure so further development is required.

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Routing flexibility

Routing flexibility is the phenomenon whereby a part may take a variety of alternative paths through the system, visiting various machines during its manufacture, and thus accommodating changes in machine availability. Machine availability changes if a machine breaks down or if a machine is already engaged in production. The purpose of a routing flexibility measure is to capture the ability of the system to absorb an event such as machine breakdown and continue to operate with minimal strain. The most likely usage would be by operations managers when allocating capacity for particular orders. In addition it is likely to be used during the system investment evaluation phase for comparison between manufacturing equipment alternatives and thus should not be technology specific. A routing flexibility measure should: increase (decrease) with increasing (decreasing) number of routes in the system; increase (decrease) with increasing (decreasing) operation capability of the machines; increase (decrease) with increasing (decreasing) machine availability; increase (decrease) with increasing (decreasing) material handling system versatility; and be comparable between systems of differing sizes. Measures for routing flexibility are plentiful in the literature. Kochikar and Narendran (1992) present a measure which adheres to the criteria listed above. It focuses essentially on a specific part-system example and evaluates the possibility of manufacturing at each stage of processing.

Operation flexibility

Operation flexibility is the "ability to interchange the ordering of several operations for each part type" (Browne et al. 1984, p.115). The purpose of operation flexibility is to raise the level of machine utilization by interchanging the sequence of operations or substituting an operation when the originally designated operation is unavailable. The purpose of an operation flexibility measure is to permit managers to decide how to allocate production capacity. Another purpose of the measure could be as a comparison between alternative designs for a prospective product. An operation flexibility measure should: increase (decrease) with increasing (decreasing) number of interchangeable operations within the part's process plan as a proportion of the total

number of operations; and increase (decrease) with increasing (decreasing) number of machines available to perform the interchanged operations. Kumar (1987) proposes an entropic style operation flexibility measure which meets the criteria well. There are some small problems with respect to interpretation of definitions in Kumar (1987) but otherwise the measure is acceptable.

3. USING THE DEVELOPMENTAL FRAMEWORK MODEL

The framework has been used as a validation tool above. We now propose using it as a development tool to create measures for two of the remaining Browne et al. (1984) flexibility types. As no satisfactory measures were found in the literature for volume and expansion flexibility we attempt these below. Development of a measure for production flexibility will not be tried due to the ambiguity of this flexibility type. A discussion of the role of production flexibility will follow.

3.1 Volume flexibility

Volume flexibility is considered to be the ability to operate efficiently, effectively and profitably over a range of volumes. Volume flexibility is attained by having lower operating fixed costs, that is by having variable costs a higher proportion of total costs. Primarily this means a lower than usual labor content, complemented by a higher level of automation which tends to be a sunk, or fixed, cost and is less volume sensitive.

Purpose

The purpose of volume flexibility is to guard against uncertainty in demand levels. Gerwin (1993) suggests the uncertainty is the aggregate product demand and the strategic objective is market share. If an enterprise has a high proportion of their total costs in fixed costs and a low proportion in variable costs (labor, material) it is less possible to widely vary production volume compared with an enterprise for which variable costs are a greater proportion of total costs. Therefore, the former enterprise will be more susceptible to market vagaries than the latter which will be able to weather

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demand declines and is less likely to fire workers. In the longer term, the company with the more volume flexible production system is the one more likely to endure economic troughs.

The objective of a measure of volume flexibility is to gauge the range of profitable volumes and the limits of this range. The measure is likely to be used in strategic planning when looking at medium to long term product marketing and analysis of potential tendering for contracts which encroach upon these time frames. For example, a company may wish to tender for a mixture of contracts which reflect differing volumes and time horizons thus minimizing the risk of falling below the lower volume profitability limit.

Criteria

A volume flexibility measure should:

- not be technology specific, that is, it should be applicable to any technology;
- be comparable between systems of differing volumes; and
- increase (decrease) with increasing (decreasing) range of profitable production volumes.

Measures

An obvious first measure is the range over which the system remains profitable. Browne et al. (1984) state that volume flexibility may be measured "by how small the volumes can be for all part types with the system still being run profitably". We suggest the range over which the system is profitable is defined by a lower limit where the volume is the breakeven point and an upper limit which is the maximum capacity of the production system. The breakeven point for the production of a single product is defined as the quantity for which the Average Total Cost (ATC) is equal to the Marginal Revenue (MR), that is when the profit is zero. We suggest the following as an initial measure for volume flexibility:

$$VF = \frac{V_R}{C_{max}} = \frac{C_{max} - N_B}{C_{max}}$$

where

- V_R is the profitability range;

- C_{max} is the maximum capacity of the system; and

- N_B is the lower limit of the profitable production range, that is the breakeven point.

This measure has a theoretical range from 0 to 1, where zero means there is absolutely no scope for demand fluctuation and 1 means that there is scope for demand changes across the entire capacity range. This definition is obviously useful for one product manufacturing scenarios only. To extrapolate this to the multi-product manufacturing setting, we must substitute the breakeven analysis for many products.

Breakeven occurs when operating income is zero, that is, there is no operating loss or operating profit. Consider the following equation:

Sales - Variable costs - Fixed costs = Operating income

That is $P_u N - C_u N - F$ = Operating Income

So for N=N$_B$ $\quad P_u N_B - C_u N_B - F = 0$

where

P_u is the unit price;

C_u is the unit variable cost;

N is the number of units; and

F is the fixed operating cost.

The breakeven point for a single product, therefore, is

$$N_B = \frac{F}{P_u - C_u} = \frac{F}{b}$$

where $b = P_u - C_u$ is the contribution margin for the product. Consequently, volume flexibility for a single product scenario is

$$VF = 1 - \frac{F}{b.C_{max}}$$

The one product case is restrictive, however, since most manufacturers have a multi-product portfolio.

Consider the situation for two products and a single capacity constraint. Here the breakeven positions form a line rather than a single point and the positions of maximum capacity also form a line (see Figure 2). The maximum capacity is specified as a line below which are all the combinations for product mix volumes of x_1 and x_2. Likewise, the breakeven is defined as a line on which every combination of x_1 and x_2 creates zero profit. The feasible production volumes are the combinations of x_1 and x_2 values below the maximum capacity line, that is the profitable and unprofitable areas. The potential production mixes are defined as

$$a_1 x_1 + a_2 x_2 \leq C_{max}$$

and the breakeven line is defined as

$$b_1 x_1 + b_2 x_2 = F$$

where b_i is the contribution margin of one unit of product i and a_i is the number of capacity units required to make one unit of product i. Therefore, profitable production lies below the maximum capacity line and above the breakeven line, as shown in Figure 2.

<Insert Figure 2>

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Consequently, unprofitable production lies below the breakeven line and the volume flexibility measure may be defined as:

$$VF = 1 - \left(\frac{Area\ of\ smaller\ triangle}{Area\ of\ larger\ triangle}\right)^{\frac{1}{2}}$$

$$= 1 - \left(\frac{\dfrac{F}{b_1} \times \dfrac{F}{b_2} \times \dfrac{1}{2}}{\dfrac{C_{max}}{a_1} \times \dfrac{C_{max}}{a_2} \times \dfrac{1}{2}}\right)^{\frac{1}{2}}$$

$$= 1 - \frac{F}{C_{max}}\left(\frac{a_1 a_2}{b_1 b_2}\right)^{\frac{1}{2}}$$

More generally, for n products we let

$$VF = 1 - \frac{F}{C_{max}}\left(\prod_{i=1}^{n} \frac{a_i}{b_i}\right)^{\frac{1}{n}}$$

The nth root is necessary for several reasons. Firstly, it is necessary to retain a dimensionless measure. Secondly, it is necessary for valid comparisons between systems that have different numbers of products. If we partition one product into n separate but identical products, then we would not expect volume flexibility to be affected by this process. Yet

$$\left(\prod_{i=1}^{n} \frac{a_i}{b_i}\right) \to 0 \ as \ n \to \infty$$

Therefore, without the root the VF measure would increase merely by adding to the complexity of the product mix.

We see that the *VF* measure is a reasonable definition. In fact, the *VF* measure:

• increases (decreases) as *F*, the fixed operating cost, decreases (increases). This

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has the effect of lowering (raising) the threshold volume where the product mix becomes profitable and hence, expanding (contracting) the profitable range.

- increases (decreases) as C_{max}, the maximum capacity, increases (decreases). This increases (decreases) the upper limit of the range, hence expanding (contracting) the profitable range.

- increases (decreases) as the b_is, contribution margins, increase (decrease). This relates to increasing (decreasing) the profitability of one or more product(s) in the mix and hence enabling a more (less) profitable range of production.

- increases (decreases) as the a_is decrease (increase). This effectively allows production of more (fewer) of the same products than before by merely using less (more) production capacity.

This measure meets the criteria above of being

- technology independent since there are no variables in the measure that pertain to FMS or any other single technology, although we imagine the cost allocation would be easier in discrete production than in continuous flow manufacturing;

- comparable between systems of differing volumes since the <u>proportion</u> of profitable capacity forms the basis of comparison, and in addition the measure is well-behaved for comparisons between systems operating with different product mix sizes; and

- compatible with the third criterion above and also behaves according our intuitive understanding for changes in product profitability and capacity usage.

3.2 Expansion flexibility

Expansion flexibility is considered to be the ability to easily add capacity or capabilities to the existing system. Sethi and Sethi (1990) describe it as "the ease with which its capacity and capability can be increased when needed". Sethi and Sethi (1990) quote several means of attaining expansion flexibility including building small production units, having modular flexible manufacturing cells, having multi-purpose

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machinery that does not require special foundations and a material handling system that can be more easily routed, having a high level of automation that can facilitate mounting additional shifts, providing infrastructure to support growth, and planning for change.

Consider the investment alternatives open to a company:

1.   invest heavily in conventional equipment to cover capacity needs in the foreseeable future.

2.   invest in a minimum efficient quantity of conventional capacity and delay additional investment until further market information is gained.

3.   invest in a minimum efficient quantity of expansion flexible capacity and delay additional investment until further market information is gained.

There are arguments for and against each alternative. For example, the advantage of (1) is that the equipment cost of a complete system is likely to be less than incremental investments that sum to the same capacity. The disadvantages of (1) include the large financial commitment at a single point in time, and the lack of information regarding level and type of demand which may result in inappropriate and over- or under-investment in equipment.

A strategic advantage that expansion flexibility endows upon a firm is that a company may not need to purchase all its equipment at the one time but can incrementally invest in the additional capital. This allows the firm to apportion funds in a way over time to minimize financial vulnerability by minimizing large up-front debt or substantially depleting cash reserves. This can somewhat insure against hostile takeover or similar threats. Also the additional incremental investment is likely to be more attuned to the company's real needs than a single forecast at the initial investment stage.

Hayes and Jaikumar (1988) argue against what they call "irrational incrementalism" with regard to CIM systems. They state that the benefits a CIM system can deliver can only result if the entire system is in place and operating. We argue that the minimum efficient quantity in expansion flexible systems includes all the infrastructure which constitutes a CIM system. The additional investments we speak of

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are ones of additional capacity or production capabilities only.

Expansion flexibility is intended to permit a company to expand production progressively, rather than purchase all equipment upfront which may place a prohibitive burden on the company. A firm could purchase capacity as required. Initially, the company could purchase enough capacity to provide minimum efficient production, and as markets expand and market share increases, the company could then purchase any additional capacity to meet new demands. These new capacity acquisitions could be undertaken in the knowledge that the implementation and integration process is likely to be less disruptive than might otherwise be if expansion flexibility were not present. Also the additional capacity may be purchased with better information than we may have at the initial investment stage.

Purpose

A measure of expansion flexibility would permit senior management to decide between investments in a non-expansion flexible (conventional) system and an expansion flexible system. The benefit of a conventional system is that the upfront costs, per capacity unit, are likely to be less than an expansion flexible system of the same size. The drawback of a conventional system is that the integration time and cost of additional capacity investments are higher than for an 'equivalent' flexible capacity.

Criteria

An expansion flexibility measure should:

- capture the dominant dimensions of comparison;
- not be technology specific;
- allow comparisons between large upfront investments of conventional systems and smaller incremental investments of expansion flexible capacity; and
- not limit the number of stages of investment in the expansion flexible scenario.

<u>Measures</u>

There is little in the literature regarding measures of expansion flexibility. Stecke and Raman (1986) suggest a measure of expansion flexibility would be a function of "the magnitude of the incremental capital outlay required for providing additional capacity: the smaller the marginal investment, the greater the expansion flexibility". However, no explicit function is proposed. Sethi and Sethi (1990) cite a measure of Jacob which depends on a ratio of differences between long-term profits of various systems.

Wirth, Samson and Rickard (1990) propose that the value of flexibility in decision analysis can be measured by the difference between the Expected Monetary Values (EMVs) of a decision with information and a decision without information. It is assumed this information is gained by delaying a decision. This approach was also the basis of Mandelbaum's (1978) work into flexibility in decision making.

We extend this line of thinking to expansion flexibility. The difference between the EMV of the flexible option (EMV_F) and the EMV of the conventional option (EMV_C) results in the expansion flexibility measure (EF), that is

$$EF = EMV_F - EMV_C$$

This model is, of course, highly dependent on the comparison between the two systems. It does not provide a 'stand-alone' measure of expansion flexibility whereby a system can be evaluated on its own merits. If does, however, capture the primary attribute of expansion flexibility, that is, its advantage over conventional systems. If the expansion flexible system offers lower costs than the conventional system, EF will exceed 0. An advantage of this measure is that it is measured in dollar, or currency, terms. This can assist in a financial evaluation and in a presentation to a board of directors who are used to dealing primarily with monetary figures. By the same token, however, the transferability of the measure to other industries and circumstances is lost since the proportions of the investment are obvious.

The model we formulate is deliberately limited for illustrative purposes. It could

be easily extended to accommodate several investment periods rather than just two. It could also accommodate additional investments in the conventional equipment, although it is trivial to show that if the marginal cost of additional conventional capacity is greater than that of flexible capacity, the flexible capacity alternative will always have a superior EMV. The marginal cost of additional conventional capacity is greater than that of the flexible capacity since the latter technology is designed for integration into existing systems, using modular equipment designs. The conventional capacity is not designed to do this and therefore, the cost of additional capacity includes the implementation and integration costs, which boost the cost above that of the flexible equivalent.

Our model assumes

- contribution margin, and hence operating costs, are equal for each of the technologies;

- only a single product is manufactured;

- the manufacturer can produce as many units as demand dictates or capacity allows, whichever is the smaller;

- capacity may be purchased in continuous amounts;

- in period 1, demand is unknown but an estimate is evaluated by a weighted sum of demand estimates; the weightings are probabilities of various 'world states' of demand for the product;

- demand is perfectly known at period 2, and managers can purchase an additional amount of capacity to exactly meet the known demand; and

- the manufacturer is risk neutral, and hence uses the expected monetary value criterion as a basis for financial evaluation.

This, in effect, means the flexible option will always manufacture to demand, whereas the conventional option will manufacture as much as demand or maximum capacity will allow.

Assume a demand set $\{D_1, D_2, ..., D_n\}$ where $D_1 \leq D_2 \leq .... \leq D_n$ with associated probabilities $p_1, p_2, ..., p_n$. If the conventional capacity purchased is C_C, then

$$EMV_C = \sum_{i=1}^{n} p_i \pi (D_i, C_C)^- - k_C C_C$$

$$\text{where } (Z_1, Z_2)^- = \min(Z_1, Z_2)$$

whilst

$$EMV_F = \sum_{i=1}^{n} p_i \pi D_i - \sum_{i=1}^{n} p_i k_F D_i$$

<Insert Figure 3>

By plotting EMV_C against C_C, as in Figure 3, we can see that the maximum EMV_C does not occur at the weighted sum of the demands but at one of the demand levels. The probability distribution used to create the curve in Figure 3 was discrete, symmetrical and increasing to a peak at the mean. There were 11 different demand values in the probability distribution. This distribution was used to approximate a normal 'bell' shaped distribution. The shape of the curve depends on the shape of the probability distribution of the demands. Whereas the weighted sum of the demand probability distribution was 750, the largest EMV_C was observed at $C_C = 870$.

<Insert Figure 4>

Figure 4 shows the demand values with their associated probabilities and where C_C lies in the continuum. Suppose C_C assumes a value between D_k and D_{k+1}. From the above definition, we have

$$EMV_C = \pi \sum_{i=1}^{k} p_i D_i + \pi C_C \sum_{i=k+1}^{n} p_i - k_C C_C$$

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Now,

$$\frac{\partial EMV_C}{\partial C_C} = \pi \sum_{i=k+1}^{n} p_i - k_C$$

Hence, if $\pi \sum_{i=k+1}^{n} p_i - k_C > 0$, *then* $C_C \geq D_{k+1}$

and if $\pi \sum_{i=k+1}^{n} p_i - k_C < 0$, *then* $C_C \leq D_k$

where $1 \leq k \leq n-1$

Thus $C_C^* = D_{j^*}$ *where* $\pi \sum_{i=j^*}^{n} p_i < k_C < \pi \sum_{i=j^*+1}^{n} p_i$

where C_C^* is the optimal level of conventional capacity.

The model illustrates the fact that expansion flexibility is of more value in situations of greater risk, or variance. For example, we approximate a normal demand distribution by a discrete one, setting $n=11$ and letting the probability distribution for demand be symmetric with mean 750 and p_i increasing from 400 to 750 and decreasing from 750 to 1100. During this exercise, a constant mean of 750 was maintained. If we now vary σ^2 we obtain the behavior of *EF* shown in Figure 5.

<Insert Figure 5>

The results, summarized in Figure 5, were obtained by calculating *EF* for various values of the variance of the probability distribution. The set of *EF* values against variance (Figure 5) was built by fixing the variance of the distribution for any one case and using an optimizing algorithm within a spreadsheet application to maximize *EF*. Since many probability distributions can exist for a given value of variance, some intervention was required by setting initial 'starting' positions of the distribution in order to achieve the maximal values of *EF* for each variance value.

EF increases monotonically with variance. This suggests strongly that *EF* is increasingly important as the certainty regarding the demand levels diminishes. In fact,

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EF is maximized for a uniform demand probability distribution, which represents the highest uncertainty under the 'normality' constraints mentioned earlier. (Removing these 'normality' constraints results in *EF* being maximized when all the probability is allocated to the extreme low and high demand values and none in between. This scenario, however, is unrealistic; it would be very unusual for the knowledge about the demand to be so polarized.)

In conclusion, the model captures the dominant characteristic of expansion flexibility, hedging against unknown demand. The expansion flexible capacity returns a higher EMV than the conventional capacity as the variance, or uncertainty, of the probability demand distribution increases. This means it would be worthwhile delaying an investment decision, or investing only part of the necessary capacity, when there is higher demand uncertainty, until a time when demand levels are more certain. This certainty may take the form of success in contract tendering, a change in government investment or protection policy, or market success of an associated (that is, positively demand correlated) product.

3.3 Production flexibility

Production flexibility was included in the original flexibility taxonomy by Browne et al. (1984). There has been little debate over its role in the flexibility arena. Browne et al. and others imply it represents the culmination of the extents or effects of the other seven flexibility types. An immediate and obvious measure is simply the sum of previous seven flexibility types. This, however, does not account for the varying importance of different flexibility types in different production systems, under different business circumstances. An improvement could be a <u>weighted</u> sum to account for these differing circumstances and situations. However, this still requires that all flexibility measures be in the same units and leaves other questions unanswered: Are these seven flexibility types the only ones that are needed to fully describe flexibility in an organization? Who decides the relative importance (weightings) of the flexibility types? What is the role of production flexibility? How are these flexibility types related?

It appears that production flexibility is an attempt to capture the holistic aspects of flexibility. Previous authors (see Chung and Chen 1989) have pursued a similar line of thought although significant gaps still exist in our understanding. Two items which may extend our understanding of production flexibility are (1) an examination of the relationships between flexibility types and (2) a listing of the "dimensions of comparison". The former is pursued in the next section and the latter discussed below.

Summary of dimensions discussion

The following taxonomy is a compilation of mutually exclusive dimensions of comparison from the literature. The definitions of the dimensions and their respective authors are:

System vs Machine: Buzacott (1982) regards machine level flexibility as a flexibility type which is contained or determined by the machine whereas a system level flexibility is one which comes from the capabilities of the entire system.

Action vs State: Mandelbaum (1978) considers how flexibility accepts change. If the ability to perform well in the new state is already there when the change takes place, state flexibility is present. If this ability is acquired by taking appropriate action after the change takes place, action flexibility is present.

Static vs Dynamic: Carlsson (1992) states "Static flexibility refers to the ability to deal with foreseeable changes (i.e. risk), such as fluctuations in demand, shortfall in deliveries of inputs, or breakdowns in the production process" and "Dynamic flexibility refers to the ability to deal with uncertainty in the form of unpredictable events, such as new ideas, new products, new types of competitors, etc.".

Range vs Response: Slack (1987) suggested managers thoughts about flexibility were

assisted by considering range and response dimensions. Range flexibility is typically regarded as the extent to which a system may adapt, whereas response flexibility captures the rate at which the system can adapt.

Potential vs Actual: Browne et al. (1984) discuss the dimensions of potential and actual flexibility, particularly with respect to routing flexibility. Potential flexibility is where the flexibility is present but is utilized only when needed, such as a part being re-routed when a machine breakdown occurs. Actual flexibility is where the flexibility is utilized regardless of the environmental status.

Short Term vs Long Term: Carter (1986) and others suggest the categories where a flexibility type influences the system or the system's environment in particular time frames, and therefore the flexibility type is considered to be either a short, medium or long term flexibility.

Table 1 contains the dimensions of comparison that are clearly dominant. Where both are clearly present, we enter "both". This table is only a guide and several of the entries are heavily qualified.

<Insert Table 1>

An interesting observation from Table 1 is that there seems to be a consistent positive correlation between the system vs machine focus and the short vs long term time frame. With only a couple of exceptions, machine focussed flexibility types tend to be ones that impact in the short term (minutes to days) and system focussed flexibility types tend to influence performance in the longer term (years). We suggest this confirms intuition as we would consider the investment of a complete system as one which is driven primarily by the strategic manufacturing mission of the company which traverses the long term time frame.

4. RELATIONSHIPS BETWEEN FLEXIBILITY TYPES

The real challenge for managers and researchers is not only to appreciate the existence of a variety of flexibility types but also the existence of relationships and tradeoffs <u>between</u> the various flexibility types. It is all very well to refer to a required level of a particular flexibility but the non-monetary costs of attaining this flexibility should be comprehended too. These non-monetary costs could include a decrease in other flexibility types which in turn could impact upon production objectives (e.g. machine utilization), service objectives (e.g. delivery timeliness) or market objectives (e.g. product availability). Understanding the relationships between flexibility types is paramount for understanding the managerial task required to manage enterprise flexibility. Given this, it is perhaps surprising there has been so little research into these relationships or tradeoffs. Of course, one reason for this may be that the relationships are complex. Some relationships seem apparent, and we will discuss some of these, but others are not obvious and change with manufacturing systems and usage.

Browne et al. (1984) presented a diagram which indicated the hierarchical relationship between flexibility types (see Figure 6). The arrow indicates "necessary for". Therefore, machine flexibility is necessary for product, process and operation flexibilities and so on. This implies that there is, for example, a positively correlated and supportive relationship of machine flexibility to product flexibility. As Browne et al. state, ideally all FMSs would possess the greatest amount possible of all these flexibility types but, of course, the cost would be prohibitive. Therefore, decisions regarding amounts desired and required by the company need to be made and information regarding the tradeoffs and relationships between the flexibility types will aid these decisions.

Gupta and Goyal (1992) are the only authors that have carried out a study using simulation into the relationships between flexibility types. Other authors have mentioned relationships they have recognized, but to date, their study is the only one that attempts to examine all the relationships in a comprehensive manner. These authors use

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computer simulation to examine the effect of different system configurations and different loading/scheduling strategies on various performance parameters. However, the performance parameters chosen are machine idle time (MIT) and job waiting time (JWT) which, we believe, places an overemphasis on the time or response aspects of manufacturing flexibility. Also we believe that by concentrating the analysis on these two parameters alone, some tenuous conclusions are drawn. Gupta and Goyal draw conclusions based purely on changing configurations and the subsequent effect on these performance parameters. For example, they state (p.532):

> let us increase the job types to ten. A statistically significant difference will indicate a change in machine idle time. If the machines incur a higher idle time while processing ten job types then it can be inferred that an increase in product variety has adversely affected volume flexibility. It may be noted that increasing product variety implies an inherent increase in the product flexibility of the manufacturing system. The system would not be able to process more job types otherwise. This demonstrates an inverse relationship between product flexibility and volume flexibility.

Following such logic, Gupta and Goyal (1992) suggest several relationships. They also examine the effects of several loading strategies and dispatching strategies. They conclude by stating: "we would like to state that this study is based on simulation and therefore it is assuming in nature. The results are system specific and may not be generalized to other systems". This indicates some reservations these authors had. The primary outcomes of the Gupta and Goyal (1992) study is the effect of different loading/scheduling schemes on machine idle time and job waiting time and secondly, upon some flexibility types.

Below, we examine some relationships between flexibility types. This work is preliminary rather than definitive and we believe much further work will be required before we gain a thorough knowledge of these relationships. We will discuss only a limited number of these relationships, with an objective of initiating further work in the area. Also, our work is qualitative and indicative of the general trend of the relationship

rather than an absolute statement. A comprehensive, empirical study into the tradeoffs and relationships is beyond the scope of this work but is likely to be, in combination with model building and simulation work, the origin of a fuller understanding. Flexibility relationships, we imagine, will be closely intertwined with managerial issues and substantial managerial insights will be developed. After our discussion, we will present a table which will summarize the qualitative relationships between the flexibility types.

Machine vs Process

Buzacott (1982) suggests there should be a positive relationship between these two flexibility types, that is, as machine flexibility increases so does "job" flexibility. He states that "in systems that are inadequately controlled so that it is not possible to exploit diversity in job routing it is possible for machine flexibility to decline with job flexibility". He proposes that the capabilities that endow a machine with machine capability also complicate it to the degree where machine reliability is a problem. Also these capabilities will contribute to a lowering of machine efficiency and hence, machine flexibility. He suggests for a single machine, machine flexibility is mostly independent of process flexibility.

Generally, we agree that a positive relationship exists here since the capabilities which underpin both flexibility types are common, namely, CNC capabilities, tool magazines and automatic tool loaders. The ability to change between operations (machine flexibility) directly assists in the ability to change between different products (process flexibility). Intuitively, an increase in the range of operations able to be performed by a machine will expand the range of products that can be produced on that machine. There are other factors which drive process flexibility and therefore there is not a directly proportional relationship, especially since machine flexibility relies heavily on the mode of usage. Several authors (Browne et al. 1984, Sethi and Sethi 1990) have suggested that machine flexibility is a foundation and prerequisite for process flexibility.

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Machine vs Product

Again, machine flexibility is acknowledged as a prerequisite for product flexibility, as it provides the foundation capabilities, that is performing several operations on the one machine. Just as this permits changing between products (process flexibility) because different products typically have different operations in their process plans, machine flexibility permits the introduction of additional products to the current product mix. This means that as machine flexibility increases, that is more operations are able to be conducted on the machine, there is a greater likelihood that the machine will be able to undertake the production of newly introduced parts, thus reflecting a higher product flexibility. Gupta and Goyal (1992) suggest that increasing the number of machines enhances the ability of the system to make "changes required to produce a given set of part types", which is machine flexibility, and also lowers the waiting times for jobs which therefore supplements "the system's capability to changeover to produce a new part, thus improving product flexibility". As mentioned previously, some of Gupta and Goyal's (1992) deductions could be called into question, although their conclusions regarding the flexibility relationships are generally sound.

Machine vs Operation

We believe machine flexibility underpins operation flexibility. By having machine flexibility, the potential for the usage of operation flexibility is amplified, although the majority of operation flexibility is drawn from the design of the part and the subsequent interchangeability of tasks. Given that any given part has the innate capabilities of operation flexibility, an increased machine flexibility will permit a greater usage of the potential. However, the converse is not true; an enhanced potential operation flexibility of a part will not increase the ability of a machine to perform additional operations. This actually reflects the directional hierarchy of Figure 6 whereby machine flexibility is "necessary for" operation flexibility, but the arrow does not aim in both directions.

Routing vs Operation

Several authors have commented that these two flexibility types are closely related but few have discussed this at length. The relationship again is unidirectional. Increasing the ability to route and reroute a part through a system, that is routing flexibility, will permit an increased ability to use the operation flexibility of a part by allowing the part to visit various machines when the sequence of tasks is changed. Providing more routes in the system allows greater versatility in task resequencing. However, endowing a part with greater operation flexibility does not, in turn, permit greater ability to reroute a part. This reflects the Browne et al. (1984) hierarchy.

Routing vs Volume

Gupta and Goyal (1992) state that they interpret an increase in the Machine Idle Time (MIT) as a reduction in the volume flexibility of the system, since volume flexibility is the ability to operate profitably at different production volumes and if there is a higher MIT, then the system is not operating as profitably as it might be. This is, we believe, a misinterpretation of the definition of volume flexibility. Volume flexibility is the extent of the production range over which the system can operate profitably and a particular usage showing a lower machine utilization does not reflect a change in the volume flexibility.

We believe this relationship could be related in that an increase in routing flexibility increases the maximum potential system capacity and hence increases volume flexibility. This is because machines that were not previously connected are now joined thus increasing the maximum potential system capacity. Another possibility is that the additional infrastructure (for example: AGVs, defined routes) that is associated with an increase of routing flexibility could in fact increase the fixed cost component of the cost structure and therefore, subsequently decrease volume flexibility, depending on how fixed costs are calculated. Therefore, it would seem that this relationship could certainly be non-linear. Although Gupta and Goyal (1992) do not explicitly state this finding of non-linearity, they find that smaller system configurations produce a positive relationship between routing and volume flexibility and larger system configurations produce a

negative relationship. A possible cause for this may be that for larger configurations, the fixed cost of the routing infrastructure could overwhelm the utilization benefits and the relationship switches from a positive to a negative orientation. Gupta and Goyal (1992) do not provide an explanation for most of the results they observed.

In summary, there has been little thorough investigation into the relationships between flexibility types, even though there is great potential for managerial insight into flexibility competitiveness. We have collected some of the "accepted" relationships and provided them in Table 2. This is not a complete listing and the blank spaces suggest an opportunity for further work. Further, these relationships will vary greatly according to a variety of environmental and usage factors.

Insert Table 2 about here.

5. CONCLUDING REMARKS

This paper has presented a framework to facilitate the development of flexibility measures by focussing the development on the purposes and criteria of the measure. This measure enables existing measures to be evaluated, as shown for machine, process, product, routing and operation flexibility. It also permits development of new measures as shown for volume and expansion flexibility. There are several pairs of 'dimensions of comparison' which can also aid this development by furthering the understanding of these flexibility types. We also raise the issue of the relationship between flexibility types. Little work has been done in this area so far but we believe it will be of substantial importance in the future to the study of manufacturing flexibility.

REFERENCES

Bolwijn, P. and Kumpe, T. (1990), "Manufacturing in the 1990s: Productivity, Flexibility and Innovation", *Long Range Planning*, 23(4), 44-57

Brill, P. H. and Mandelbaum, M. (1989), "On measures of flexibility in manufacturing systems", *International Journal of Production Research*, 27, 5, 747-756

Brill, P. H. and Mandelbaum, M. (1990), "Measurement of adaptivity and flexibility in production systems", *European Journal of Operational Research*, 49, 325-332

Browne, J., Dubois, D., Rathmill, K., Sethi, S. P. and Stecke, K. E. (1984), "Classification of flexible manufacturing systems", *The FMS Magazine*, April, 114-117

Buzacott, J. A. (1982), "The Fundamental Principles of Flexibility in Manufacturing Systems", *Proceedings of the First International Congress on FMS*, 13-22

Carter, M. F. (1986), "Designing Flexibility into Automated Manufacturing Systems", *Proceedings of the Second ORSA/TIMS Conference on FMS*, Ann Arbor, Michigan, 107-118

Carlsson, B. (1992), "Management of Flexible Manufacturing: An International Comparison", *OMEGA*, 20, 1, 11-22

Chung, C.H. and Chen, I.J. (1989), "A Systematic Assessment of the Value of Flexibility from FMS", *Proceedings of the Third ORSA/TIMS Conference on FMS*, Cambridge, Massachusetts, 27-34

de Groote, X. (1992), "Flexibility and Product Diversity in lot-sizing models", *Working Paper No. 92/05/TM INSEAD*, 1-17

De Meyer, A., Nakane, J. and Ferdows, K. (1989), "Flexibility: the next competitive battle - The Manufacturing Futures Survey", *Strategic Management Journal*, 10, 135-144

Dixon, J. R. (1992), "Measuring manufacturing flexibility: An empirical investigation", *European Journal of Operational Research*, 60, 131-143

Gerwin, D. (1993), "Manufacturing Flexibility: A Strategic Perspective", *Management Science*, 39(4), 395-410

Gunasekaran, A., Martikainen, T. and Yli-Olli, P. (1993), "Flexible Manufacturing Systems: An investigation for research and applications", *European Journal of Operational Research*, 66, 1-26

Gupta, Y. P. and Goyal, S. (1989), "Flexibility of manufacturing systems: Concepts and measurements", *European Journal of Operational Research*, 43, 119-135

Gupta, Y. P. and Goyal, S. (1992), "Flexibility trade-offs in a random flexible manufacturing system: A simulation study", *International Journal of Production Research*, 30, 3, 527-557

Hayes, R. H. and Jaikumar, R. (1988), "Manufacturing's Crisis: New Technologies, Obsolete Organizations", *Harvard Business Review*, Sep-Oct, 77-85

Jaikumar, R. (1986), "Postindustrial Manufacturing", *Harvard Business Review*, Nov-Dec, 69-76

Kochikar, V. and Narendran, T. (1992), "A framework for assessing the flexibility of manufacturing systems", *International Journal of Production Research*, 30, 12, 2873-2895

Kumar, V. (1987), "Entropic measures of manufacturing flexibility", *International Journal of Production Research*, 25, 7, 957-966

Mandelbaum, M. (1978), "Flexibility in Decision Making: An Exploration and Unification", Ph.D. Thesis, Department of Industrial Engineering, University of Toronto, Canada

Sethi, A. K. and Sethi, S. P. (1990), "Flexibility in Manufacturing: A Survey", *International Journal of Flexible Manufacturing Systems*, 2, 289-328

Slack, N. (1987), "The Flexibility of Manufacturing Systems", *International Journal of Operations and Production Management*, 7, 4, 35-45

Stecke, K. E. and Raman, N. (1986), "Production flexibilities and their impact on Manufacturing Strategy", Working Paper No.484, School of Business Administration, The University of Michigan, 1-36

Voss, C.A. (1988), "Success and failure in advanced manufacturing technology", *International Journal of Technology Management* 3(3), 285-297

Wirth, A., Samson, D. A. and Rickard, J. (1990), "The Value of Flexibility and Control in Decision Analysis", *International Journal of Information and Management Science*, 1, 2, 107-113
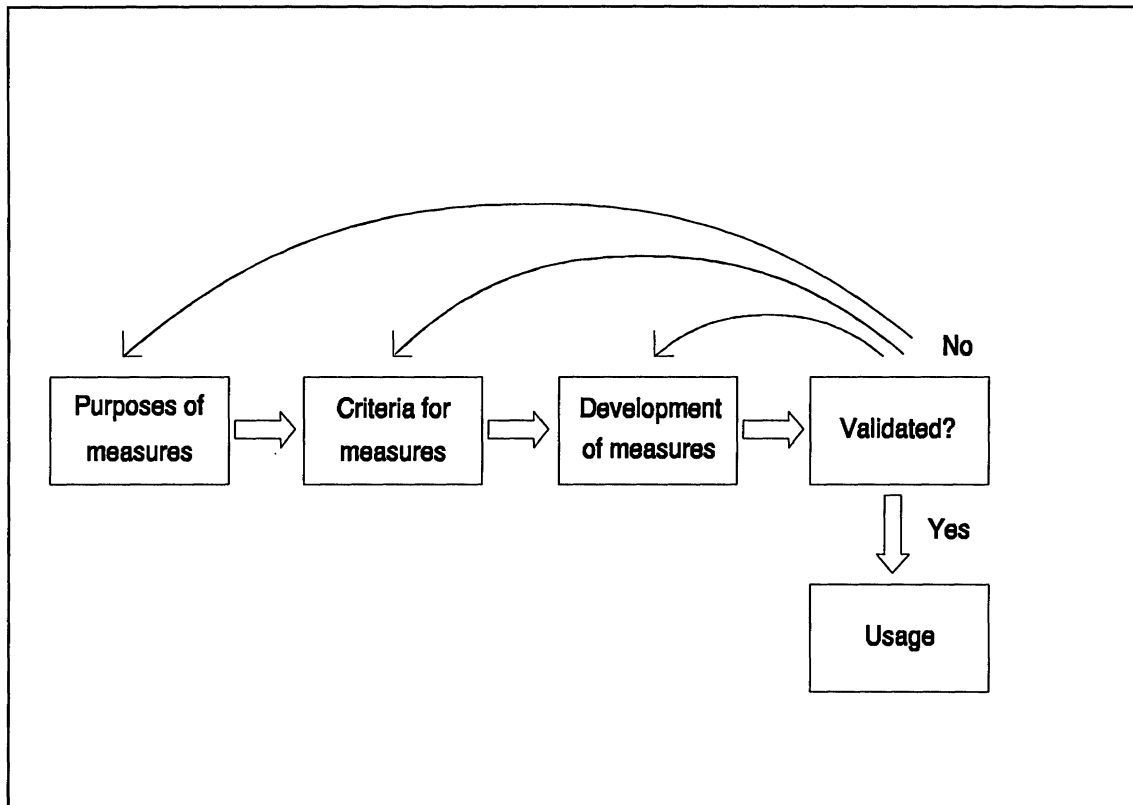
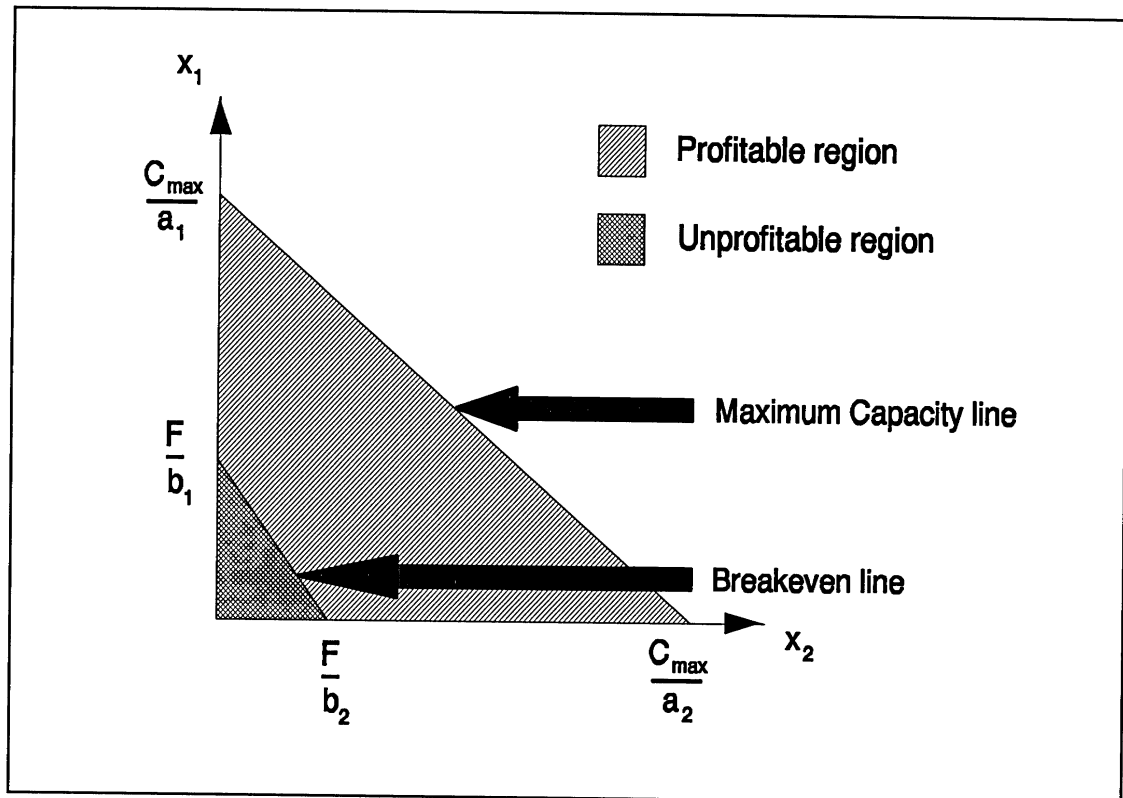**Figure 1** Flexibility measure development model.

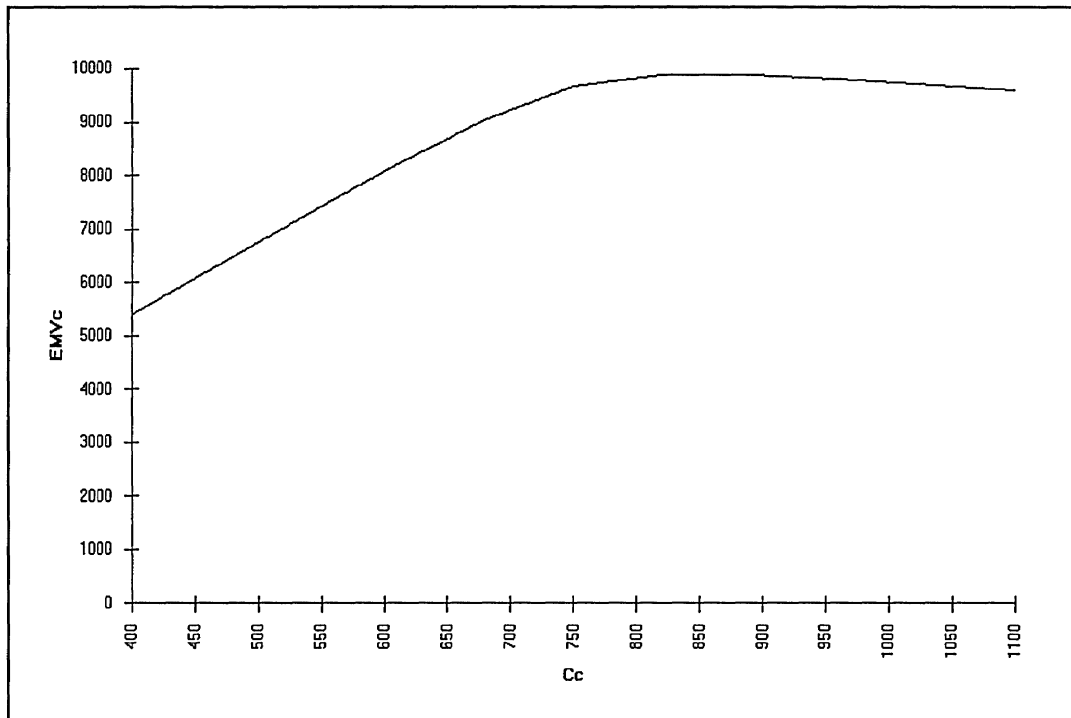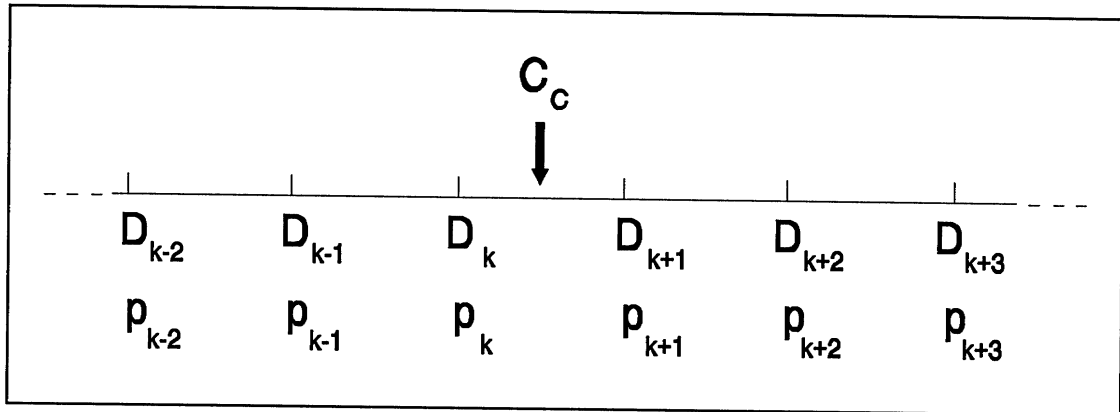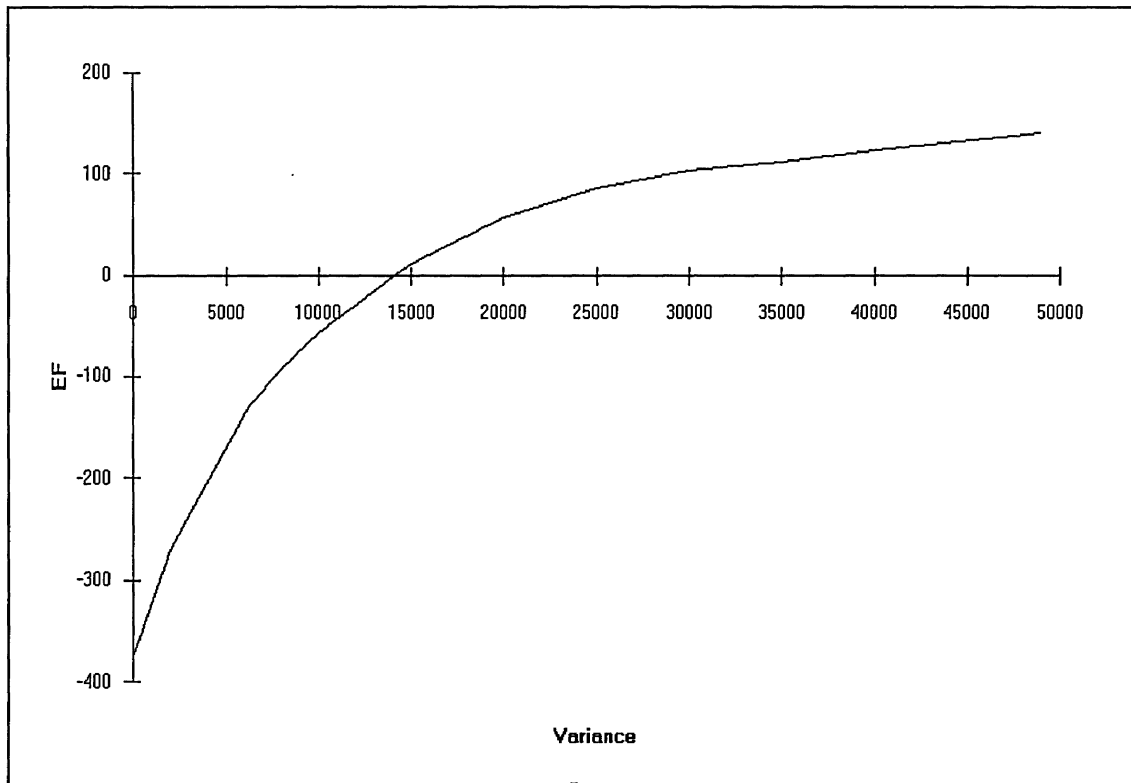**Figure 2** Volume flexibility diagram for two products
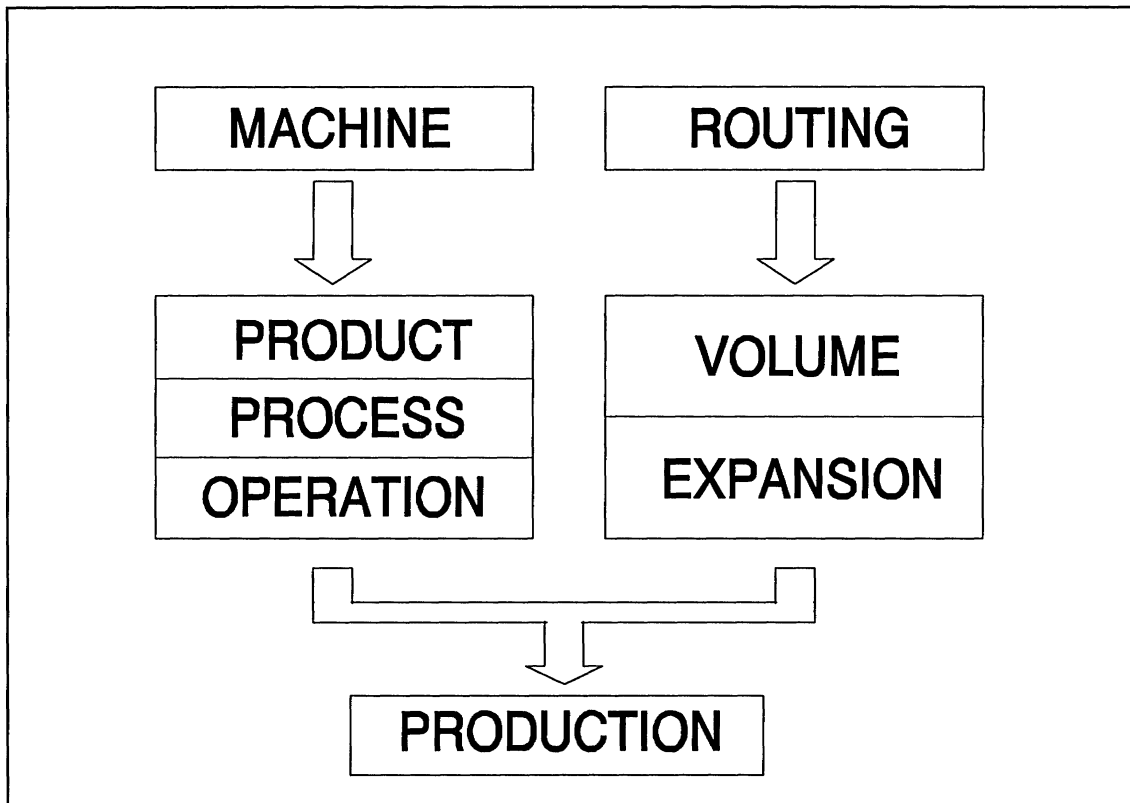
Figure 3 EMV_C vs C_C

Figure 4 Demand line showing C_c between D_k and D_{k+1}.

Figure 5 Expansion flexibility as a function of variance of the demand probability distribution.

Figure 6 Hierarchical relationship between flexibility types (source: Browne et al. 1984)

Table 1 Taxonomy of dimensions of comparison.

Dimensions	Flexibility types						
	Machine	Process	Product	Routing	Volume	Expansion	Operation
System vs Machine	Machine	Machine	Mixed	System	System	System	N/A
Action vs State	State	State	Action	State	Action	Action	State
Static vs Dynamic	Static	Static	Dynamic	Static	Static	Static	Static
Range vs Response	Both	Both	Both	Both	Both	Both	Both
Potential vs Actual	Actual	Actual	Actual	Usage	Actual	Actual	Both
Short, Medium, Long term	Short	Short	Medium	Short-Medium	All	Long	Very Short

Table 2 Descriptive relationships between flexibility types

	machine	process	product	routing	volume	expansion	operation	production
machine		++	++	++	--		++	++
process			++	++	--			
product					--			
routing					+-		++	
volume								
expansion								
operation								
production								

Key: ++ positive relationship; -- negative relationship; +- mixed relationship