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Manufacturing flexibility: a literature review

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In this article an attempt is made to classify the vast literature regarding manufacturing flexibility; the aim is to contribute to the conceptual systemization of the debate, whose richness plays witness of the abundance of themes and the difficulty of obtaining a unitary and univocal framework. The literature on manufacturing flexibility is analysed according to a scheme which considers six different aspects: (1) definition of flexibility, (2) request for flexibility, (3) classification in dimensions of flexibility (the authors group the various classifications proposed according to different logics: horizontal, vertical, temporal, by the object of the variation, mixed), (4) measurement of flexibility, (5) choices for flexibility, (6) interpretation of flexibility.

1. Introduction

In this article an attempt is made to classify the vast literature regarding manufacturing flexibility. This theme has been considered by numerous authors, according to different approaches and considering the various dimensions of flexibility. The richness of the debate, which covers no less than a decade of academic and managerial publications, plays witness to the abundance of themes and the difficulty of obtaining a unitary and univocal framework. The aim of the present article is to contribute to the conceptual systemization of the material, which often only focuses on the classification of flexibility performances.

Despite the fact that the literature on the subject is vast and articulated (Suarez and Cusumano 1991), a certain ambiguity in the definitions still persists. 'The confusion and ambiguity about a concept that often represents a critical competitive capability seriously inhibits its effective management' (Upton 1994); 'Ten or 15 years ago, quality was much like flexibility is today: vague and difficult to improve yet critical to competitiveness... Flexibility is only beginning to be explored... It means different things to different people' (Upton 1995b).

Among the causes of unclearness, the authors note the consideration of flexibility as internal (to the manufacturing system) or otherwise external (namely, how it is perceived by the customer); the difficulty of limiting the flexibility of the manufacturing system (how must the suppliers' flexibility be directed?); the evaluation of flexibility in potential or effective terms; the emphasis on the ability to adapt (reactive) or change (proactive).

The literature on manufacturing flexibility is analysed in the following paragraphs according to the scheme proposed in table 1, which considers six different aspects inherent to the theme in question. Each article usually deals with one or more aspects, starting from the definition of flexibility in relation to the general, company,

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1. Definition of flexibility	• General • With direct reference to the production
2. Factors which determine the request for flexibility	• Environmental uncertainty (both internal and external) • Variability of products and of processes
3. Classification of flexibility (dimensions)	• Horizontal (or by phases) • Vertical (or hierarchical) • Temporal • By object of the variation • According to more variables (or mixed)
4. Measurement of flexibility	• Direct indicators • Indirect indicators • Synthesis indicators
5. Choices for flexibility	• Design or technological • Organizational/managerial
6. Interpretation of flexibility	• Competitive priority versus performance • Aim ('ex ante') versus result ('ex post') • Potential versus effective • Strategical versus operational • Defensive versus offensive • Aimed at obtaining further performances

Table 1. Scheme proposed for the classification of the aspects of manufacturing flexibility, found in the literature.

and manufacturing context. Often the reasons that motivated the request for flexibility are investigated, and flexibility itself is classified in different ways, which the authors grouped according to different logics: (1) horizontal or by phases, (2) vertical or hierarchical, (3) temporal, (4) according to the object of the variation (volume, mix, characteristics of the product or of the manufacturing process, etc.), (5) mixed or according to more different variables. On the other hand, there are few specific studies on the measurement of flexibility (which indicators should be used, how to use the measures obtained, etc.). Finally, many works deal with the choice of determinant in obtaining flexibility (which can be distinguished in design or technological choices and organizational/managerial ones) and how flexibility is understood (competitive priority or performance, performance as an 'ex ante' objective or as a result to be measured, that is 'ex post', potential or effective performance, with a strategical or operational value, defensive or offensive, aimed at obtaining further performance).

2. Definition of flexibility

The definitions of manufacturing flexibility found in literature either directly refer to the firm's context or derive from general definitions of flexibility born in other disciplines (such as the biological-evolutionary one, the anthropological one, that of the theory of systems, etc.). The origin and application of the definitions of flexibility are summarized in table 2 and then briefly described.

From a general point of view, flexibility can be understood:

(1) As characteristic of the interface between a system and its external environment (Correa 1994). In this case, flexibility acts as a filter, buffering the

		Application of the definition	
		Other disciplines	Firm context
Origin of the definition	Other disciplines	• As a characteristic of the interface between a system and its environment • As a degree of homeostatic control and dynamic efficiency • As a capability of adaptation or change	Range of states reachable and time for moving (determined by demand variety and uncertainty)
	Firm context	—	• Low costs for changing (economic approach) • Changing 'without disorganization' (organizational approach) • Volume, mix, product, process changes (operational approach) • Competitive priorities and businesses changes (strategic approach)

Table 2. Origin and application of the definitions of flexibility.

system from external perturbations. Flexibility thus functions as an absorber for uncertainty. The external perturbations are characterized by: (1) measure, (2) frequency, (3) novelty, (4) certainty;

(2) As a degree of homeostatic control and dynamic efficiency of a system (Mariotti 1995). Reference is made to a cybernetic system, namely one which incorporates mechanisms of measurement, control and regulation aimed at homeostasis, that is to say at the preservation of an existing state in the presence of exogenous changes. Flexibility is thus mainly understood as a degree of cybernetic adaptation.

According to Mariotti, this latter model is often oversimplified, since: (1) it does not take into account the fact that adaptation takes place over a period of time during which all decisions may be reconsidered; (2) it is difficult to list 'ex ante' all the possible future states (to foresee the necessary feedback); (3) homeostatic balance is preserved by consuming resources, in other words flexibility is not free, and costs/times differ according to the variations.

The concept of system complexity is linked to two dimensions: uncertainty and time. Uncertainty can be—according to Simon (1976)—informative (a lack of information) and of knowledge (subjective limits of those who take decisions). Time intervenes in terms of sequentiality (see the correlated concept of irreversibility of decisions) and cumulativeness (in other terms the accumulation of knowledge which can improve decision-making performances).

The author believes that as the complexity of the system gradually increases, it is necessary to substitute the concept of homeostatic control with that of 'inter-time and information adaptation' (where the players are always passive but are able to give 'value to the options' and modify this 'value' in time) and then of 'dynamic efficiency' (if the players are able to influence external changes).

On the basis of views still taken from the systems theory of control, Leeuw and Volberda (1996) treat flexibility as a two-dimensional concept: (1) first, flexibility is seen as a *management task* and the concern is the *extensiveness of control capacity* with respect to the environment (i.e. the organization is defined as a controlling organ and the environment as a target system, so flexibility means the ability to successfully control the environment); (2) flexibility is seen as an *organization design task* and the concern is the *controllability* of the organization from the environment (i.e. the environment is defined as a controlling organ and the organization as a target system, so high flexibility corresponds with low controllability from the environment).

This two-dimensional conception of flexibility creates a *paradox*: an organization must possess some procedures which enhance its flexibility in order to avoid becoming rigid, but it must also be anchored in some way in order to avoid chaos. Rather than accepting the dichotomy of *preservation* and *change*, this paradox implies that organizational flexibility incorporates both change and preservation. Consequently, management has to deal with a constructive *tension* between that which must be changed and that which it is necessary to preserve; a tension—for example—between the need for managers to question and challenge vs the preservation of core values and organizational mission.

(3) As capability of adaptation/change.

Flexibility, considered as a general ability to adapt/change, was considered and extended to firms in rather similar terms both by Mandelbaum (1978) and by Slack (1983, 1987) and concerns the range of states reachable and time for moving as a consequence of the variety and the uncertainty of demand (table 2).

Mandelbaum (1978) distinguishes between:

- state flexibility;
- action flexibility.

The former is the ability to work in spite of changes in the operative conditions (it allows the system to remain 'stable'). The latter is the ability to take actions in front of a change, and in particular to pass from one type of business to another, in a short period of time and with low costs.

Slack (1983) assumes this concept, distinguishing between:

- range flexibility;
- response flexibility.

The former is an almost static aspect, typically measured over a long period, with time and cost as elements of friction. The latter is a dynamic aspect, involving the change from one state to another, and is typically measured over a short period and without notable changes in cost.

The two different types of flexibility—range and response—can be considered in the context of the company and placed together with the two main factors which induce the request for flexibility: the variety (of products and processes) and the uncertainty of the demand. Volume flexibility (whether short or long-term, that is to say of response and range) is the result of situations characterized by a high level of uncertainty and a low variety; on the other hand, product flexibility (typically long-term or of range) is present when the variety offered is great and uncertainty is low.

Mix flexibility and delivery flexibility concern both situations of great uncertainty and low variety and those with great variety and not much uncertainty.

The difference in the two types of flexibility (range and response) may also explain the different behaviours of manufacturing systems with different manufacturing planning and control systems: in their investigations, Slack and Correa (1992) found that a plant managed with a MRP has usually greater range flexibility but lower response flexibility than a JIT plant; moreover, the differences between MRP and JIT plants are generally greater for range flexibility than for response flexibility.

Slack (1987) concludes that the flexibility performance can be analysed as value range or number of states reachable:

- in absolute;
- within a certain time;
- within a limited cost;
- within a certain limit of time and cost.

It follows that, though being the intrinsic dimension of flexibility that of time (ability to move quickly from one state to another, in other words to 'change in order to adapt'), flexibility is completely described by:

- the range of possible states;
- the time needed to move from one state to another;
- the cost needed to change the state.

However, as there is a correlation between the cost and the time, so great that it often means a choice of 'trade-off', only two dimensions may be considered: the range of the states and the time for change.

Slack's hypotheses (Slack 1983, 1987) are taken up by Upton (1995a), who considers flexibility as being the result of various dimensions, each of which appears in different time intervals and with three elements typifying them:

- range;
- mobility (in relation to the 'transition penalities for moving within the range');
- uniformity (of performances other than cost—such as quality—within the range).

Flexibility is therefore defined as 'the ability to change or react with little penalty in time, effort, cost, or performance'.

Flexibility has also been studied with Petri nets, which are graphs with 'states' (or 'conditions') and 'transitions' (or 'events'); each transition has certain input states and output states: flexibility is a function of the time needed to reach these states (Barad and Sipper 1988).

The notion of flexibility as a typical concept of the theory of the firm (table 2) seems to have been first introduced by Stigler in 1939 (the *economic approach*). He studied flexibility in terms of the slope of short-run cost curves; he stated that the flexibility is greater the flatter are marginal cost curves and average cost curves, where costs are a function of production volume. This type of flexibility is known as volume flexibility.

Perhaps the most rigorous analytical study on volume flexibility has been done by Mills (1984). Mills assumed the following quadratic cost function: $c(q) = \alpha + \beta q + q^2/2\delta$, $\alpha, \beta, \delta > 0$, where c is total cost and q is production volume.

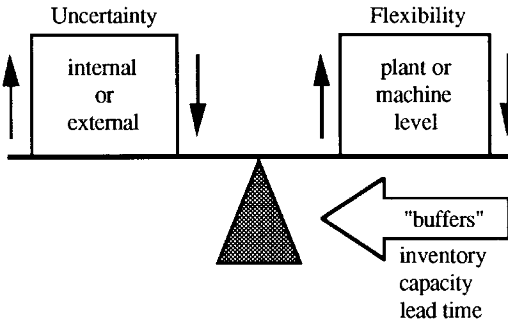

Figure 1. Balance between uncertainty and flexibility (Newman *et al.* 1993).

Another notion of flexibility directly originated in the firm context regards the *organizational approach*, which treats models of organization that permit to operate responsively in a rapidly changing environment, including labour flexibility as an individual ability (Atkinson 1985). Particularly important are the contributions of Burns and Stalker (1961), with the concept of the 'organic' structure as opposed to the 'mechanistic' one, and Mintzberg (1979), with the concept of 'adhocracy'.

But in the management literature the greatest debate regards manufacturing flexibility (the *operational approach*).

Zelenovich (1982) defines manufacturing flexibility as the ability of a manufacturing system to adapt to changes in environmental conditions and in the process requirements. This definition is important, since for the first time it takes into account both the exogenous and the endogenous nature of flexibility: the former as consequence of the market's demand, the latter as exploitation of the opportunities offered by technological innovations.

Newman *et al.* (1993) define flexibility as a fundamental instrument for dealing with uncertainty. The counterbalancing action of flexibility towards uncertainty may be represented (figure 1) by the two plates of a balance, one of which represents flexibility, and the other uncertainty (both external—of the demand or the supply—and internal—failures, lack of materials, delays). Flexibility may be defined:

- for each machine (therefore on technological grounds);
- for each plant (therefore on managerial grounds).

The fulcrum of the balance may be moved—with obvious consequences on the balance—by acting on the 'buffers' of the manufacturing system (inventory, reserve capacity, over-estimating of lead times); therefore, in the case of increased uncertainty, it is possible to counterbalance the latter either by increasing flexibility (for example by means of a greater integration between the various departments and between production and the other functions of the company) or by 'buffers', moving the fulcrum towards the plate representing uncertainty (for example, by operating with more inventories).

This may, however, create a vicious circle: by acting on the fulcrum, the complexity of the system may increase, an therefore also uncertainty (for example, longer lead times may cause congestion and uncertainty on source availability). Furthermore, internal uncertainty is not independent from external uncertainty; it is sufficient to mention supply and the integration with the suppliers: the uncertainty of the supply (external) also has consequences on the uncertainty of operations within the firm (in terms of quantity and quality of the materials to be processed).

Garud and Kotha (1994) use 'the brain as a metaphor to generate insights on how firms might design flexible production systems, by employing practices that promote distributed processes occurring in a parallel manner and creating a learning system able to evolve incrementally from initial inputs'.

Finally there is an emerging approach (the *strategic approach*) which considers the ability of a firm to change its competitive priorities (Hayes and Pisano 1994) or businesses (Stalk *et al.* 1992). Harrigan (1985) says that strategic flexibility refers to the ability of firms 'to reposition themselves in a market, change their game plans, or dismantle their current strategies when the customers they serve are no longer as attractive as they once were'.

3. Request for flexibility

The literature on the reasons behind the request for flexibility is rather vast, however, there appear to be two main factors (Correa 1994):

- environmental uncertainty;
- variability of the products and processes.

In the first case, flexibility coincides with the ability to deal with the unexpected, both within the manufacturing system (e.g. machine failures) and outside (e.g. the demand and the supply). In the second case, flexibility is the ability to offer a variety of products and to carry out different manufacturing processes.

Mascarenhas (1981) defines flexibility as the ability to cope with instability caused by the environment.

Buzacott (1982) claims that any attempt to estimate the flexibility of a manufacturing system on a global level must follow an analysis of the nature of the changes faced by the system; these changes are be definition external, and concern: (1) products; (2) mix; (3) the quantities typifying the offer, which depend on: (a) the technological level, (b) the market's demand, (c) the policy of the firm. According to Buzacott, the changes within the company must be considered as 'inconveniences' (machine or plant failures, variability in work times due to congestion of the manufacturing system, lack of materials to be processed, etc.).

Some authors (such as Miller *et al.* 1992) claim that the request for flexibility mostly comes from the customers, and therefore they talk of 'customer-driven flexibility'. The influence of product and production flexibility on market strategy is investigated by Easton and Rothschild (1987).

Other authors list various factors which require flexibility. For example, Palaniswami (1994) defines five factors:

(1) Products (wideness of the range, number of parts, etc.);
(2) Manufacturing processes (availability of general purpose machines, reduced set-up times for the machines, etc.);
(3) Planning and control (policies of lotting, scheduling, storage, etc.);
(4) Human resources (training, trade-union relations, etc.);
(5) Relations with the suppliers (comakership policies, etc.).

Summarizing, the conditions which mostly determine the request for flexibility which emerge from the literature, can be listed as follows:

(1) The variability of the demand (random or seasonal);
(2) Shorter life-cycles of the products and technologies;
(3) Wider range of products;
(4) Increased customization;
(5) Shorter delivery times.

4. Classification of flexibility

The direct ways of classifying flexibility and the subsequent numerous dimensions found in the literature appear to confirm the thesis of a vast and articulated concept (Hyun and Ahn 1992). 'Flexibility is a complex, multi-dimensional, and hard-to-capture concept' (Sethi and Sethi 1990). It therefore becomes fundamental to find some variables for the classification, that is to say the different logics for interpreting the various dimensions of flexibility.

In our opinion, four different classification logics can be found, although often the taxonomies presented are the result of mixed logics:

(1) Horizontal or by phases;
(2) Vertical or hierarchical;
(3) Temporal;
(4) By the object of the variation.

Among the mixed logics, the most common is that which takes into account both the time and the object of the variation (for example: short-term flexibility relative to volumes or mix; medium–long-term flexibility relative to product and process innovation, to the expansion of manufacturing capacity, etc.).

Table 3 summarizes the most significant contributions, according to the order previously described, which will be discussed in detail in the following paragraphs.

4.1. *Horizontal classification of flexibility*

Horizontal classification of flexibility is aimed at limiting the analysis (Harrison 1993). It makes reference to the single manufacturing stages, and, in a wider sense, to all the phases which constitute the 'value chain' (Porter 1985), which also include: upstream—design and purchasing; downstream—distribution and customer service. More simply, one may distinguish between internal flexibility (product/process design and production flexibility) and external flexibility (purchasing and distribution flexibility).

Lynch and Cross (1991) take into consideration two components of flexibility: internal and external; the latter is relative to the need to meet the requirements of customers, whereas the former to the need to meet them in an efficient manner. Therefore, in Lynch and Cross's pyramid (on the left of which there are the performances perceived externally, whereas on the right there are those within the firm), flexibility is in a central position: on its left there is customer satisfaction, which is an external performance, and on its right there is productivity, which is an internal performance. There are also lower-level performances: product quality and delivery reliability constitute the customer satisfaction; delivery reliability and short process lead times improve the flexibility; short process lead times and process quality and cost influence the productivity.

Kim (1991) analyses flexibility along the 'value chain'. Similarly to Porter's 'cost drivers', 'flexibility drivers' are found which determine the flexibility of the nine

1. Horizontal classification (or by phases)	• Value chain (Kim 1991) • Internal/external (Lynch and Cross 1991) • Extended to the suppliers (Kumpe and Bolwijn 1988) • Extended to service (Silvestro 1993)
2. Vertical (or hierarchical) classification	• By levels (Buzacott 1982, Gerwin 1982, Slack 1987, Swamidass 1987, Sethi and Sethi 1990, Gupta 1993, Mair 1994)
3. Temporal classification	• Of adaptation/design (Zelenovich 1982) • By time horizons (Merchant 1983)
4. Classification by objects (volume, mix etc.) of the variations, in relation to other variables	• Environmental uncertainties (Gerwin 1982) • FMS features (Browne *et al.* 1984) • Perturbations of the manufacturing system (Azzone and Bertelè 1989, 1991) • Technological and managerial features of the manufacturing system (Brandolese 1990) • Functions of the firm involved (Chen *et al.* 1992, de Groote 1994a) • Other performances (Dixon *et al.* 1990, Bartezzaghi and Turco 1989)
5. Mixed-logic classification	• Temporal/by objects (Barad and Sipper 1988) • Vertical/by objects (Taymaz 1989, Benjaafar and Ramakrishnan 1996) • Horizontal/vertical (Nilsson and Nordahl 1995).

Table 3. A summary of the contributions on flexibility classification.

value-generating macro-activities (between brackets are reported some drivers for each type of macro-activity):

- infrastructures (drivers such as simplifying procedures and information systems adaptation);
- management of human resources (drivers such as an effective selection and training);
- technological development (drivers such as product/process integration);
- purchasing (drivers such as Electronic Data Interchange—EDI);
- in-bound logistics (drivers such as just-in-time deliveries);
- operations (drivers such as Flexible Manufacturing Systems—FMS);
- out-bound logistics (drivers such as the reduction of shipping documents);
- marketing and sales (drivers such as computer-integrating with production);
- services (drivers such as the existence of a data-base on the problems and solutions related to service).

A firm is flexible when it can modify its value chain by varying the relative composition of the activities forming the chain and the combination of factors within each activity, so as to influence its position in relation to the competitors, thus gaining a competitive advantage, should the internal and external environmental conditions vary.

Kumpe and Bolwijn (1988) focus on purchasing flexibility, and consider the operative integration with the suppliers as one of the most efficient ways to obtain manufacturing flexibility. However, Bartlett and Ghoshal (1989) observe how the choice of the suppliers usually occurs following cost criteria (or quality ones) rather than the flexibility performances warranted by the suppliers, and this is most probably due to the objective difficulties in measuring flexibility.

Some authors extend the concept of flexibility downstream, and also consider flexibility in customer service (technical assistance, training, etc.—Silvestro 1993) as well as delivery flexibility (which concerns volume and mix—De Toni and Tonchia 1996). The two types of flexibility—relative to delivery and services offered—may differ in terms of level of performance.

4.2. *Vertical classification of flexibility*

The vertical (or hierarchical) classification of flexibility concerns the degree of detail of the analysed object: flexibility may be estimated in relation to the single resources of a system ('micro level') or to the whole system (aggregate flexibility or 'macro level').

Buzacott (1982) and Gerwin (1982) distinguish between *resource flexibility* (machines and human resources) and *production system flexibility* as a whole (which varies according to the type of production and the managerial criteria).

Gerwin (1987) in particular describes four levels at which flexibility may be analysed and measured:

- plant and machine level;
- production function and work department level;
- product (or product line) level;
- global level of the firm (extending the concept to other functions, such as distribution, purchasing, design, maintenance, etc.).

When referring in particular to the Honda case study, Mair (1994) distinguishes three levels of flexibility:

- a 'micro' level, characterized by the flexibility of workers, machines and organization;
- a level of factory flexibility;
- a level of flexibility of the corporation's network ('the global network of flexi-factories').

Swamidass (1988) on the other hand makes a distinction between *machine-level* and *plant-level* flexibility: the former is exclusively technological, whereas the latter also takes into account the firm's skills, the procedures adopted, managerial systems, etc.

In this sense, as other authors have also stated (Barad and Sipper 1988), *system flexibility* depends on the 'aptitude' of its components (materials, machines, and workers), their 'interconnections' and the operative and control criteria.

Slack (1987, 1988) introduces the concept of 'flexibility hierarchy'; four categories of flexibility are described concerning:

- manufacturing resources;
- the aims of production;
- the production function;

- the whole company.

The flexibility of *manufacturing resources* may derive from: (1) the technology followed, (2) the work power, (3) the services supporting production ('infrastructures'), Barad and Sipper (1988), Gupta and Goyal (1989) and Gupta and Somers (1992) distinguish between flexibility of the technology and human resources (known as 'structural flexibility') and 'infrastructural flexibility' (of the systems, the procedures and the practices which integrate and co-ordinate the operations).

Flexibility as a *production aim* coincides with: (1) product flexibility (regards new products launching or modifying pre-existing ones, both in qualitative terms and in terms of different features/functionality of the products); (2) mix flexibility (both in terms of range and of response—see § 2); (3) volume flexibility (regards the capability of varying the production volume); (4) delivery flexibility (regards the capability of changing the scheduled dates).

Flexibility of the *production function* determines delivery reliability and customer-oriented offer. Furthermore, production flexibility increases the *overall* flexibility of the company (which also involves research and development, design, marketing, distribution, etc.). For details on this point see also Chen *et al.* (1992).

Sethi and Sethi (1990), after having considered eleven types of flexibility based on the object of variation (see § 4.4), articulate them on three levels:

- component or basic flexibilities (machine, material handling, and operation flexibility);
- system flexibilities (process, routeing, product, volume, and expansion flexibility);
- aggregate flexibilities (program flexibility, deriving from the process, and routeing ones; production flexibility, deriving from the process, routeing, and product ones; market flexibility, deriving from the product, volume, and expansion ones).

Gupta (1993) focuses on classifying uncertainty into hierarchical levels based on the magnitude and scope of changes; there are four different levels:

- *machine* ('machine flexibility is the ability to process a variety of different parts effectively');
- *cell* (the building blocks of machining cells are: workers, machines, load-unload equipment, intra-cell movement devices, and the cell controller);
- *plant* (measurement of flexibility at this stage involves determination of costs of coping with uncertainty—Falkner (1986) argues that 'if a manufacturing plant is flexible, manufacturing costs ought to be relatively stable over widely varying product mixes and levels of total volume');
- *corporate*.

4.3. *Temporal classification of flexibility*

Zelenovich (1982) was the first to consider short-term or *adaptation flexibility* as well as medium–long-term flexibility, which is typically related to *design adequacy*. A similar distinction between manufacturing and design (respectively) flexibility is proposed by De Meyer *et al.* (1989).

The first complete classification of flexibility on temporal bases was given by Merchant (1983), who makes a distinction between:

- instantaneous flexibility (the ability to immediately select the most suitable work centre for carrying out the operation required by the work cycle of a certain part);
- very short-term flexibility (the ability to modify the sequence and mix of the parts produced);
- short-term flexibility (the ability to modify certain design specifications of the parts of the products);
- short- to medium-term flexibility (the ability of the system to work at the maximal levels of productivity when production volumes are varied);
- medium-term flexibility (the possibility to add or eliminate parts from the mix of parts being produced);
- medium- to long-term flexibility (the possibility to modify the manufacturing capacity by adding or eliminating work centres);
- long-term flexibility (the possibility to adapt the system to new types of products or mix of components).

The classifications of flexibility on temporal logic found in literature usually follow the above-mentioned lines.

4.4. *Classification of flexibility by the object of variation*

The classification of flexibility by the object of the variation for which flexibility is considered, is the most common one found in the literature.

Skinner (1985) considers flexibility according to three dimensions, in relation to the objects of variation:

(1) the process;
(2) the product;
(3) the production volume.

Buffa (1984) considers process flexibility in relation to set-up times, and product flexibility in relation to product variety. Macbeth (1985) specifies product flexibility both in relation to variety and product innovation, whereas volume flexibility is linked to the possibility for the customer to vary the dimension of the order. Beckman (1990) simply distinguishes between *process* flexibilities (they improve the ability of a production system to cope with internal or supply contingencies, such as machine failures) and *product* flexibilities (these are more relevant to product competition in dynamic markets, and increase the range of products a production system can process and/or reduce the cost and time required to switch production resources from one product to another).

Gerwin was the first to mention various dimensions of flexibility in a specific manner (1982) and in the following years (1987 and 1993) to relate them to the different types of environmental uncertainties which caused them; Gerwin distinguishes various types of flexibility:

(1) Relative to the *materials*, which can be defined as the ability to deal with unexpected variations in the inputs, and measured through the dimensional tolerances and maximum variances tolerated in the chemical–physical properties of the materials;
(2) Relative to the *volume*, which can be defined as the ability to deal with variations in the aggregate demand, and measured by the ratio between the average variation of the product volume and the maximum product capacity

(volume flexibility can also be measured as the ratio between the investments necessary to widen the production and the global level of the investments in plants—Gustavsson 1984);

(3) Relative to the *products* ('modification flexibility'), which can be defined as the ability to meet the demands of the market in terms of product specifications, and measured by the number of changes in the design within a certain period of time, or by the ratio between investment necessary to modify the existing production and the global level of investments in plants (these are small changes in the product, else reference is made to 'change-over flexibility' which concerns product innovation);

(4) Relative to the *mix*, which can be defined as the ability to meet the market's requirements in terms of variety of products supplied in a certain time, and measured by the wideness of the range (a similar definition is proposed by Chatterjee *et al.* 1984); another indicator for mix flexibility was proposed by Buzacott (1982) as the ratio between number of processed parts by a machine or group of machines in a given period of time and total number of workable parts, or the number of general purpose machines present;

(5) Relative to the *change-over*, which takes into account the ability to vary in time the production mix, in relation to the life cycle of the single products ('while mix flexibility is the ability of a manufacturing process to produce a number of different products at the same point in time, change-over flexibility is the ability of a process to deal with additions or subtractions from the mix over time');

(6) Relative to the *standard cycle* ('re-routeing flexibility'), measured by the number of possible routeing options, important for dealing with machine failures (an alternative measure of 'cycle flexibility' is given by the decrease in the rate of global productivity due to failures–Buzacott 1982).

In 1987, Gerwin adds one more type of flexibility to those listed in 1993, that is *sequencing* flexibility, which takes into account the uncertainty related to the deliveries of the suppliers. In 1993, Gerwin proposed a conceptual framework which also included a 'meta-level' of flexibility known as *strategical* flexibility.

A classification often cited in literature is that by Browne *et al.* (1984) which, taking into account the Flexible Manufacturing Systems (FMS), considers eight different types or dimensions of flexibility:

(1) *Machine* flexibility: 'the ease of change to process a given set of part types'; measures are for example:
  - set-up times required by a machine to pass from one type of process to another; they include the change of tool, the positioning of the part and the substitution of the part-programme;
  - the time necessary to change a broken or worn-out tool;
  - the time necessary to modify the set of tools on the machine in order to produce a different sub-set of parts;
  - the time required to set up the new equipment, etc.;

(2) *Product* flexibility: 'the ability to change to process new part types'. It can be measured by the time required to pass from one mix of parts to another. Product flexibility is the most important from a marketing point of view: the rapid launch of new products with competitive costs allows an effective response to the market changes;

(3) *Process* flexibility: 'the ability to produce a given set of part types'. A measure of this flexibility is given by the number of parts which can be produced (Browne *et al.* (1984) consider process flexibility for each machine, while Buzacott (1982) does not distinguish this type of flexibility, that the author also calls 'job flexibility', for each machine or group of machines). For these first three dimensions of flexibility, the object of the variation is: *machine set-up*, the *product mix*, and the *part processed*, respectively;
(4) *Operation* flexibility: 'the ability to interchange ordering of operations on a part'. In most cases operations sequencing is rigid, but for certain operations it is arbitrary. Not deciding 'ex ante' which will be the next process or machine notably increases flexibility. The decisions are taken in real time by the control system according to the state of the plant;
(5) *Routeing* flexibility: 'the ability to process a given set of parts on alternative machines'. In other words, the ability of a flexible system to work in a sub-optimal manner. A measure of this flexibility is given by the number of parts which can still be produced and the decrease of productivity. There are two ways to obtain routeing flexibility: the part may be processed in a routeing which does not require the use of the machines out of service, or the operations may be done with other units. This flexibility may be: (a) potential—the processing routeings are fixed, and only in the case of failures are the alternative ones used; (b) effective—the same part is processed with different routeings, independently of failures;
(6) *Volume* flexibility: 'the ability to operate profitably at varying overall levels'. It can be measured by the volume increase/decrease which causes the average costs to reach the maximum acceptable value;
(7) *Expansion* flexibility: 'the ability to easily add capability and capacity'. This type of flexibility can be determined by the dimensions in terms of capacity that the system can reach;
(8) *Production* flexibility: 'the universe of part types that can be processed'. This type of flexibility can also be defined as the potential mix of the parts that can be produced.

Browne *et al.* (1984) also stress relationships among flexibility types: in particular there are two basic types of flexibility: *machine* flexibility (that determines product, process and operation flexibilities) and *routeing* flexibility (that determines volume and expansion flexibilities). Overall *production* flexibility is determined by these two basic types of flexibility.

On the basis of the Browne *et al.*'s classification, Sethi and Sethi (1990) distinguish eleven types of flexibility, adding to the previous ones: *material handling* flexibility ('the ability to move different part types efficiently for proper positioning and processing through the manufacturing facility'), *program* flexibility ('the ability of a system to run virtually untended for a long enough period') and *market* flexibility ('the ease with which the manufacturing system can adapt to a changing market environment') and with a different consideration of the machine flexibility ('which refers to the various types of operations that one machine can perform without requiring a prohibitive effort in switching from one operation to another').

Azzone and Bertelè (1989) introduce the concept of *elementary* flexibilities, so defined since they can be measured by indicators independent from each other; the following may be considered elementary flexibilities:

(1) *Production* flexibility (the wideness of the range of products which can be obtained with the existing resources);
(2) *Product* flexibility (the ability to modify the resources of the firm in order to launch a new product);
(3) *Operational* or *technological* flexibility (the ability to introduce operations with limited costs to the firm);
(4) *Mix* flexibility (the ability to vary the mix of products in quantitative terms, without further costs);
(5) *Volume* flexibility (the ability to vary the volume of products without remarkable consequences on production costs);
(6) *Expansion* flexibility (considered in relation to the costs for the expansion of the production capacity).

The first three flexibilities are caused by *qualitative perturbations* (with '*range*' perturbation for the production flexibility, *small* and *large* perturbations respectively for the product and technological flexibility), while the other three are caused by *quantitative* perturbations (with '*range*' perturbation for the mix flexibility, *small* and *large* perturbations respectively for the volume and expansion flexibility).

In Azzone and Bertelè (1991) there is a classification according to six dimensions, but instead of mix and technology flexibility there are, with different meanings, process and cycle flexibility, which are related to set-up time and ability to operate in the presence of machine failures respectively.

Suarez *et al.* (1991) identify four types as the major constructs that capture the dimensions of flexibility required in a production system:

(1) *Volume* flexibility;
(2) *Mix* flexibility;
(3) *New product* flexibility;
(4) *Delivery-time* flexibility.

Parthasarthy and Sethi (1992) subsume these four types of flexibility under:

(1) *Speed* flexibility (it refers to the rapidity with which a production system can deliver finished products when required, change its volume rate and modify its product mix);
(2) *Scope* flexibility (it refers to the breadth of products, including the degree of customization, that a production system offers).

Brandolese (1990) makes a distinction between *flexibility* (the software or managerial feature of the manufacturing system as a whole) and *versatility* (the intrinsic or hardware feature of the manufacturing system, a feature of the machines and plants which represents a necessary condition to obtain flexibility).

As regards *flexibility*, three dimensions may be taken into consideration:

(1) The ability to modify a pre-established production plan (changes in time);
(2) The ability to sort a wide range of products (changes in quantity, both of the single products, and in terms of total production);
(3) The ability to engineer/industrialize a new product (changes in the quality of the offer).

Versatility, on the other hand, has two main dimensions, which may also be independent (e.g. a given plant may be more reconfigurable and less convertible than another):

(1) *Reconfigurability* (which takes into account the vastness of the set of operations which can be carried out, the efficiency with which they may be executed, and whether the various operations of the set are compatible with each other in terms of cost and set-up times);
(2) *Convertibility* (which takes into account the problems of setting up a plant when industrializing new products, including the necessary changes in the plant, layout and auxiliary systems).

Tincknell and Radcliffe (1996) distinguish between:

(1) *Flexibility*—the ability to cope with the uncertainty of change effectively (is the effect of the uncertainty counteracted?) and efficiently (are the cost, time and effort required low?);
(2) *Versatility*—the ability to change intentionally, or to exist in different states, following standard procedures (acting in a versatile way is acting in a standard way, e.g. changing the mix of parts being produced in a standard manner);
(3) *Capability*—the physical range of functions or envelope of operations that a machine, sub-system or system can perform (it represents the potential to respond to change if ideal control and perfect management strategies are used; to achieve versatility a system relies on its underlying capability).

Chen *et al.* (1992) consider an *aggregate flexibility of the system*, deriving from three types of flexibility which refer to the production and marketing functions of the firm, and its infrastructural features:

(1) *Production* flexibility, which includes the following types of flexibility:
    (a) *machine* flexibility (the ability to carry out different operations with limited set-up times);
    (b) *process* flexibility (the ability to process a given set of components with different processes, operation sequence and materials);
    (c) *routeing* flexibility (the possibility to follow alternative routeings);
    (d) *manpower* flexibility;
    (e) *material handling* flexibility (dependent on internal transportation systems);
    (f) *programming* flexibility;
(2) *Marketing* flexibility, which includes the following types of flexibility:
    (a) *product* flexibility;
    (b) *volume* flexibility;
    (c) *mix* flexibility;
    (d) *expansion* flexibility;
(3) *Infrastructural* flexibility (the flexibility of the organization).

Finally, some authors such as Dixon *et al.* (1990) and Bartezzaghi and Turco (1989), who classify flexibility by objects, also consider it in relation to other performances.

Dixon *et al.* (1990) propose the following classification of flexibility:

(1) *Flexibility associated to quality*:

  - (a) relative to the materials (the ability to deal with variations in the purchased materials);
  - (b) relative to the output (the ability to make products with different quality requirements);
- (2) *Flexibility associated to the product*:
  - (a) launching new products;
  - (b) changing pre-existing ones;
- (3) *Flexibility associated to service*:
  - (a) deliveries (the ability to change the content of the order or the delivery date);
  - (b) volume (the ability to vary the quantity of the aggregate production);
  - (c) mix (the ability to modify the variety of products in a given period of time with limited added costs);
- (4) *Flexibility associated to costs*, the flexibility in the use of resources (materials, manpower, capitals).

This distinction is important, since not only do the indicators differ, but also the strategic aims and the actions to pursue them. According to the authors, each firm should therefore clearly define which are the priority types of flexibility.

Particularly interesting is also the work by Bartezzaghi and Turco (1989), who, after having pointed out four key performances (productivity, quality, flexibility and service) for each manufacturing system, remark on the relations between these performances, flexibility and productivity in particular.

The dimensions of flexibility found by Bartezzaghi and Turco are the following:

- (1) *Product* flexibility (measured in terms of output variety in a given period of time, and by the costs and time necessary to launch a new product);
- (2) *Volume* flexibility (in the short and medium term it is related in particular to 'manpower flexibility', in the long term it is also known as 'expansion flexibility' since it is related to the times and costs to increase the manufacturing capacity of the plant);
- (3) *Mix* flexibility;
- (4) *Promptness* (the ability to vary delivery dates and/or internal planning).

Bartezzaghi and Turco remark on the fact that the various types of flexibility may be in trade-off with each other (for example: a manufacturing system which is flexible in relation to the volume may not be so in relation to the mix or the introduction of a new product). This is also sustained by Upton in his article in Harvard Business Review (Upton 1995b).

Other authors (Warnecke *et al.* 1981, Gustavsson 1984, Mandelbaum and Buzacott 1990) have studied the relationships between flexibility, productivity, and investment: for example, it has been seen that, for equal levels of productivity, the investment required to increase the degree of flexibility of a manufacturing system has a more than quadratic trend.

4.5. *Classification of flexibility according to more than one variable (mixed classification)*

As previously mentioned, although classifications of flexibility according to one variable (phase, level of analysis, time horizon or the object of the variation) are the most common in literature, mixed logics are also adopted. The most common are those which consider both the object of the variation and time, or both the object of the variation and level of analysis (vertical logic).

Barad and Sipper (1988) consider nine classes of flexibility: eight of these are those proposed by Browne *et al.* (1984), and the ninth is the so-called 'transfer' flexibility (defined as the ability to process parts using different machines). The 'routeing' flexibility considers the mix presently in production and depends on 'process' and 'transfer' flexibility (which are both independent from the actual mix). The authors distinguish between components of a short–medium-term flexibility and those of a long-term one:

(1) *Short–medium-term* flexibility:
   (a) *machine* flexibility;
   (b) *process* flexibility;
   (c) *transfer* flexibility;
   (d) *routeing* flexibility;
   (e) *operation* flexibility;
   (f) *volume* flexibility;
(2) *Long-term* flexibility:
   (a) *product* flexibility;
   (b) *production* flexibility;
   (c) *expansion* flexibility.

Taymaz (1989) uses the 'hierarchical structure of flexibility' to derive different types or dimensions of flexibility. There are three levels of analysis: *component level*, *operations level*, and *system level*:

- at the most concrete *components* level, there are three basic types of flexibility, each corresponding to the sets of components in a production system: *machine* flexibility, *routeing* (*material handling*) flexibility, and *control* flexibility. These flexibility types can be defined and compared without any reference to production characteristics (product mix, production runs, etc.) and they are determined 'a priori' by design;
- at the *operations* level, machine, routeing, and control flexibilities with their interconnections to other features of components determine other types of flexibility such as *product*, *process*, *mix*, *volume*, *expansion*, etc. These flexibility types must be evaluated for some definite production characteristics, that is, their measurements are production dependent;
- finally, there is *overall production flexibility* at the most abstract, *system* level.

The 'flexibility hierarchy' proposed by Benjaafar and Ramakrishnan (1996) does not name different levels of analysis but it simply divides *system* flexibility between:

(1) *Product-related* flexibility (it refers to the variety of manufacturing options associated with a product)—its dimensions are:
   (a) *operation* flexibility (it relates to the possibility of performing an operation on more than one machine),
   (b) *sequencing* flexibility (it relates to the possibility of interchanging the sequence in which required manufacturing operations are performed),
   (c) *processing* flexibility (it relates to the possibility of producing the same manufacturing feature with alternative operations or sequences of operations);

(2) *Process-related* flexibility (it is a characteristic of the process and refers to the capability of the process to adjust to various operating conditions and/or to assume different functions)—its dimensions are:
   (a) *processor* flexibility (its sub-dimensions are: *machine* flexibility, *fixture* flexibility, *tooling* flexibility, *material handling* flexibility, and *labour* flexibility),
   (b) *mix* flexibility (*short-term*, *medium-term*, and *long-term* flexibility),
   (c) *volume* flexibility,
   (d) *layout* flexibility,
   (e) *component* flexibility.

A mixed logic is also that adopted by Nilsson and Nordahl (1995), who propose a framework with a distinction between internal and external flexibility (horizontal logic) and between strategic flexibility and resource flexibility (vertical logic).

5. Measurement of flexibility

Notwithstanding the importance and constant interest raised by flexibility in academic and managerial circles, the measure of flexibility is still an under-developed subject, both for its multi-dimensionality and the lack of indicators for its direct measurement (Cox 1989). 'The measures proposed are somewhat naive and arbitrary (Sethi and Sethi 1990). 'Inspite of the need, no well-accepted operationalizations exist' (Gerwin 1993). 'A very limited work has been done on investigating the robustness of the suggested measurements' (Chen and Chung 1996).

Since it is difficult to measure manufacturing flexibility, it is often hard to financially justify investments aimed at increasing the flexibility of a manufacturing system (Hill and Chambers 1991) without turning to expensive solutions such as FMS—flexible manufacturing systems—on which there is a vast literature (see § 6).

Figure 2 reports a diagram proposed by the authors to classify the various measures (or indicators) of flexibility:

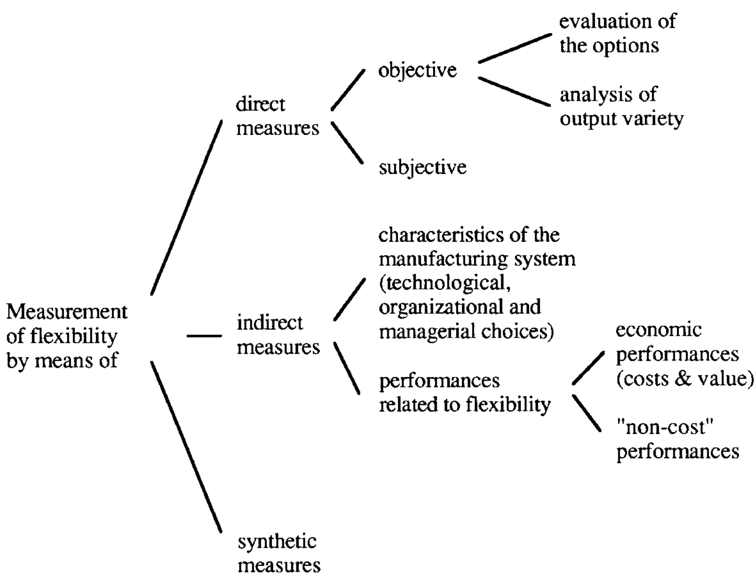

Figure 2. The authors' proposal for classifying the measures of flexibility.

- *direct* (objective or subjective);
- *indirect* (relative to certain features of the manufacturing system which can determine flexibility or performances related to flexibility);
- *synthetic*.

Direct objective measures mostly consist in:

(1) The evaluation of the possible options in a certain instant ('decisional approach'—Jones and Ostroy 1984, Mandelbaum and Buzacott 1990, Ramasesh and Jayakumar 1991, Kogut and Kulatilaka 1994). Yao (1985) and Kumar (1987) propose 'entropy' as an indicator for flexibility, since it takes into account the variety of options and is characterizing in terms of stochastics and degree of freedom. Stockton and Bateman (1995) claim that measuring flexibility in terms of probability enables quantitative relationships to be established between different levels of flexibility;
(2) The analysis of the variety of certain output features (Fiegenbaum and Karnani 1991); this is clearly an 'ex post' type of approach (that is to say that it is necessary to have data on the output over time); moreover this measure does not show which were the causes of variability and if the latter was a desired performance or a form of adjustment with consequent undesired costs (not always being easy to determine—e.g. the lost opportunities to earn due to lower levels of flexibility).

On the other hand, *direct subjective measures* are perceptual, and are based for example on Likert's scales: opinions are given on various aspects concerning flexibility, expressing the degree of agreement/disagreement over precise statements (Gerwin and Tarondeau 1989).

Given the difficulties in defining flexibility performances in a direct manner, various authors (Gerwin 1987, Slack 1987, Silvestro 1993) propose the use of *indirect indicators*. The indirect measures are taken considering:

(1) The characteristics of the manufacturing system which allow manufacturing flexibility (for this reason they are also known as 'choices'—see § 6); these characteristics can either be technological (e.g. the availability of manufacturing overcapacity, the entity of set-up times, etc.) or organizational–managerial ones (e.g. job enrichment/enlargement and team working, modular planning, etc.).

    Ettlie et Penner-Hahn (1994) suggest three (indirect) measures of manufacturing flexibility: (a) number of unique parts scheduled, (b) number of part families (a part family includes a set of parts similar in form, function, material, or machine operation), (c) average changeover time (it is the average elapsed time to switch between two parts), and their ratios.
(2) The performances which are in some way related to flexibility (see § 7), and which may be: (a) economical (of cost or value); (b) 'non-cost' (such as product development times, delivery times, quality, customer service). The former is also known as 'economical approach': an attempt is made to quantify costs/revenues in relation to the different hypothesized flexibility levels (Gupta and Buzacott 1989), or to estimate the economic losses due to slow or non-existing adjustment to the changed environmental conditions (Buzacott 1982, Son and Park 1987). Gupta (1993) proposes the 'value of flexibility' as a surrogate measure of flexibility, because 'any measure of flexibility has to be

user or situation specific; this explains the existence of many different measurement schemes and also the lack of universal acceptance of any one scheme'; the flexibility value 'provides a one-dimensional and easy-to-understand measure, but also it allows simultaneous valuation of flexibility for the particular situation or firm'.

A different approach is that which considers a 'non-cost' performance criterion other than flexibility (such as productivity increase/decrease in the presence of changes in the mix or machine failures). In both cases (economical and 'non-cost' approach), since the various 'non-cost' performances are inter-dependent between each other and the economical results, it is not possible to find direct causal relationships between flexibility and a single variable.

Since flexibility has various dimensions (see § 4), only partial measures of the flexibility of a manufacturing system may be taken; therefore in a second moment there must be procedures of *synthesis*, in order to obtain a single aggregate indicator which takes into consideration the different types of flexibility. The synthesis of the measures of flexibility is considered in the vertical classification of flexibility (see § 4.2).

The synthesis of the measures can be considered both as a measurement (in the sense of a process which produces a measure, even if it is a synthetic one) and as a measure (although it is synthetic). The *synthesis* of the measures requires rules for the composition of elementary measures in aggregate measures, and the elementary data must be complete, homogeneous and phased in order to be operationalized together (Tonchia 1995).

Brill and Mandelbaum (1989), on the other hand, introduce the function $F_{M,T}$:

$$F_{M,T} = \frac{\int_{-r}^{+r} e(r)\,dr}{\bar{e}2r}$$

defined as the machine's flexibility M in relation to its task T, as the working condition r of the machine varies; $\bar{e}$ is the value of the machine's performance in standard work conditions $r = 0$, whereas $e(r)$ is the value of the performance within the range $\pm r$.

A typical machine performance is its productivity (pieces processed per time unit or per energy consumed) or the quality of the work (number of rejects and amount of scraps).

The machine performance considered is that which best allows one to evaluate the achievement of the given task. The standard work condition is that for which machine performance is maximized ($\bar{e} = \max e(r)$). Flexibility is therefore measured as the percentage in performance loss due to a perturbation Δr of the standard work condition.

This type of measurement gives rise to at least three practical problems:

- a clear and univocal definition of machine performance;
- the calculation of the trend of the function $e(r)$ for all the values within the range (to be found empirically);
- the definition of a function F_{M^*,T^*} of the values of the functions $F_{M,T}$ relative to each machine, where task T^* (the task of the plant, where a plant is a set of several machines) is not simply the sum of the single tasks T.

Jordan and Graves (1995) develop a measure for the process flexibility in a given product–plant configuration: this is called $\Pi(M)$, the maximal probability over all groupings or sets of products M that there will be unfilled demand for a set of products while simultaneously there is excess capacity at plants building other products.

The relative analytic support and justification are based on the concept of 'chain': 'a "chain" is a group of products and plants which are all connected, directly or indirectly, by product assignment decisions'. Jordan and Graves argue that it is not necessary to have very high plant flexibility to cope with product-mix uncertainty at the corporate level when the set of products is pre-specified: a small amount of flexibility added in the right way—creating fewer longer 'chains' that better balance the assignment of products to plants—'can have virtually all the benefits of total flexibility'.

6. Choices for flexibility

Another field of research relative to manufacturing flexibility concerns the choices (techniques, methods, and criteria), also called 'determinants' (Tidd 1991), taken to obtain flexibility. Many are the articles on this subject, and most appear to agree upon dividing the choices into:

- *design* choices, also known as technological, plant, or 'hardware' choices;
- *organizational–managerial* choices, also known as 'software' choices.

The vast literature on flexible manufacturing systems (FMS) deals in particular with the former type of choices: among the articles, the following deserve to be mentioned: Buzacott and Shanthikumar (1980), Hutchinson and Holland (1982), Suri (1985), Warnecke and Steinhilper (1985), Buzacott and Yao (1986), Miltenburg (1987), Adler (1988), Hundy and Hamblin (1988), Babbar and Rai (1990), MacCarthy and Liu (1993), Kaighobadi and Venkatesh (1994).

Nelson (1986) identifies flexibility with the adoption of FMS. Most authors tend instead to agree with Jaikumar's (1986) view, who claims that the use of a FMS is the concrete application of a strategy aimed at obtaining manufacturing flexibility by means of technological choices (on this matter, see also Goldhar and Jelinek 1985).

Organizational–managerial choices are the object of studies on managerial criteria and the most suitable organizational solutions for obtaining flexibility (Carlsson 1989, 1992); Upton (1995b) argues that the flexibility of the plants depends much more on people than on any technical factor—equipment and computer integration. Jennings and Seaman (1994) demonstrate that organizations with a high level of adaptation have an organic structure (instead of a mechanistic one) and adopt a prospector strategy (instead of a defender strategy). Furthermore, there are also studies which take into account the influence of the country system where the firm operates, culture, education and training, relations with trade-unions, etc. (Gerwin and Tarondeau 1989).

7. Interpretation of flexibility

Flexibility can be considered in many ways, according to the different uses, aims, or functions in relation to which it can be analysed; in particular:

- as *competitive priority* (or *key successful factor*) versus *performance* (De Meyer *et al.* 1989, Nakane and Hall 1991);

- as *performance aim* (therefore 'ex ante') versus *performance result* (therefore 'ex post') (Slack 1983, Swamidass and Newell 1987, Slack and Correa 1992);
- as *potential* versus *effective performance* (Upton 1994);
- as *strategical* versus *operational fact* (Gustavsson 1984, Frazelle 1986, Evans 1991, Kim 1991, Chambers 1992, Stalk *et al.* 1992, Gerwin 1993, Hayes and Pisano 1994, Sanchez 1995);
- in a *proactive* (or *offensive*) sense rather than in a *reactive* (or *defensive*) one (Slack 1987, Swamidass 1988, Gerwin 1993, Newman *et al.* 1993, Jennings and Seaman 1994);
- *in relation to other performances*, and in particular to obtain other performances (Warnecke *et al.* 1981, Gustavsson 1984, Gerwin 1987, Slack 1987, Bartezzaghi and Turco 1989, Dixon *et al.* 1990, Mandelbaum and Buzacott 1990, Chen and Adam 1991, Correa 1994, Benjaafar 1994, Benjaafar and Ramakrishnan 1996).

These points will now be briefly discussed.

Flexibility is considered a *competitive priority* or key successful factor (KSF) in these times of great turbulence in the demand, constant quest for better products/processes and competitors who have made their availability of flexible human and technological resources a source of competitive advantage. For this reason flexibility is treated as a competitive priority which must be pursued rather than a quantity to be measured (i.e. a performance).

At a lower level, of performance rather than competitive priority, a given *performance* may be considered in terms of *aim* (and therefore 'ex ante') or in terms of *result obtained* (and therefore 'ex post').

Another interpretation is that which distinguishes between *potential* performance (an estimated value) and *effective* performance (a measured value). Potentiality may also be considered from a point of view of probability (the probability of obtaining a certain performance).

Nilsson and Nordahl (1995) make a distinction between:

- the requested flexibility;
- the replied flexibility;
- the potential flexibility.

Moreover, it is also possible to distinguish a *strategical flexibility*, relative to the firm's ability to successfully vary the mix of its competitive priorities or businesses, from an *operational* one, which must instead be understood as the ability to positively react to the internal and external changes as these occur.

This distinction is sometimes correlated with the time horizon within which flexibility is estimated: short-term and therefore operational; medium–long-term and therefore strategical. Gustavsson (1984) claims that flexibility has different aspects since it is required when problems occur, the latter rising in different time horizons: (1) operational problems (machine failures, lack of materials), (2) tactical problems (such as those caused by changes in the plans or in the production levels), (3) strategical decisions (relative to investments in new plants and machinery due to an expansion in the production or the launch of a new product). According to Frazelle (1986), long-term flexibility coincides with the ability to manage the most appropriate process techniques over time.

Chambers (1992) considers flexibility within manufacturing strategy, following Hill's scheme (1989) for manufacturing strategy development. Product flexibility and volume flexibility, the volume being either aggregate or specified by the mix, are relative to the first two stages (definition of the firm's aims and the marketing ones); those types of flexibility which have a direct impact on price, quality and service performances (Chambers mentions set-up, quality and delivery flexibility—delivery flexibility is required when the customer's lead time is inferior to production lead time or when the customer changes the amount or times of the orders) are relative to the third stage (definition of the qualifying aims with respect to the competitors); process and planning flexibility are relative to the fourth and fifth steps (choice of the processes and infrastructures).

Hayes and Pisano (1994), in their famous article published in Harvard Business Review, define the strategical flexibility as the capability to change the firm's strategy with the competencies selected, developed, and exploited according to the previous strategies.

Sanchez (1995) asserts that strategical flexibility depends jointly on the *resource flexibility* and the *coordination flexibility* of the firm in using its available resources; the concept of coordination flexibility helps identify critical inter-dependencies between the flexibilities. Resource flexibility is greater when there is a larger range of alternative uses to which a resource can be applied, and when the costs and difficulty of switching and the time required to switch from one use to another one are lower, while coordination flexibility regards both the firm's product strategy and the firm's configuration of resources along the value chain.

From a strategic point of view, flexibility may be intended in a *proactive* (*offensive*) sense or in a *reactive* (*defensive*) one. Gerwin (1993) thoroughly investigated this distinction, and succeeded in defining four different strategies which influence flexibility:

- *adaption* strategy (reactive);
- *re-allocation* strategy (proactive);
- *banking* strategy, namely that for accumulating reserve capacity (reactive/proactive);
- strategy *reducing/controlling uncertainty* (proactive).

The first three strategies require flexibility, whereas the last one limits the need for flexibility; in this case, managers may find alternative solutions (Slack 1987): outside the firm by trying to stabilize the demand, and within the firm by using certain techniques such as preventive maintenance. Should a certain degree of operational flexibility be necessary, it should be a feature of the external subjects with which the firm interacts (suppliers, subcontractors, etc.).

From a defensive point of view, the measurement of flexibility can be correlated to the pursuit of 'economies of scope' (Nemetz and Fry 1988), typical of FMS (Goldhar and Jelinek 1983), which allows, for a certain production level, reductions in costs in relation to certain product mixes (Oelve 1985).

The interpretation of flexibility in a defensive/offensive key can also be found when analysing service flexibility (Correa and Gianesi 1994); it is possible either to try to manage the sources of uncertainty and variability (by means of forecasting techniques, discounts on bookings, etc.) or deal with uncertainty and variability with flexibility (relative to the range of services offered, times and places of delivery, packaging, accessory services, etc.).

Flexibility may be a first-order performance just as quality, cost and time, but also be a means to *obtain other performances* (Correa 1994). Slack (1987), as well as claiming that flexibility is not a performance required in equal measure by different competitive environments and for different manufacturing techniques, also notes that it does not directly lead to results which can be measured in economic terms, but is a means to obtain other performances, and can therefore be judged for its impact on the latter; flexibility is thus a means to improve:

- delivery reliability;
- plant and manpower productivity;
- the ability to be 'customer-oriented'.

Flexibility as a means to obtain other performances is also a way of classifying the flexibility itself (see the end of § 4.4).

de Groote (1994b) proposes a framework based on the identification of three elements: technologies, environments, and a performance criterion for the evaluation of different technologies in different environments; the framework hinges upon the distinction between two complementary properties: 'flexibility'—a property of the technology—and 'diversity'—a property of the environment (the word 'diversity' is used to convey the general idea of variability, variety, or complexity). Then, de Groote discusses three propositions: '(1) the overall performance of the system is improved if the more diverse environment is allocated to the more flexible technology; (2) an increase in the diversity of the environment makes it more desirable to select a more flexible technology; (3) an increase in the flexibility of the technology makes it more attractive to operate in a more diverse environment'.

8. Conclusions

Having given a summary of the literature, we would like to add some brief considerations on the various aspects analysed (definition of flexibility, means to obtain it, interpretations, classification, determinants, measures).

A first distinction must be made between 'state' flexibility and 'action' flexibility (Mandelbaum 1978). The former is the ability to work despite the changes in the work conditions. The latter is the ability to react to the changes, and in particular to pass from one operational state to another in a short time and with limited costs.

Slack (1983 and 1987) developed these concepts and proposed a 'range' flexibility and a 'response' flexibility, the former being substantially static (the range of the possible states), while the latter is dynamic (the time of the response).

Several authors agree upon a distinction between 'static' and 'dynamic' flexibility. As the system becomes increasingly more complex the importance of dynamic flexibility becomes more marked than that of static flexibility. The concept of complexity is relative to two dimensions: uncertainty and time. Uncertainty may be informative (lack of information) and cognitive (subjective limits of the agents taking the decisions). Time intervenes in terms of sequentiality (for the irreversible nature of the decisions) and cumulativeness (for the increasing wealth of knowledge which can improve decision-making performances).

The distinction between static and dynamic flexibility also allows one to discriminate the means to obtain flexibility. The means which ensure static flexibility are substantially those related to the technologies used (such as FMS, which are designed once the system's degrees of freedom are defined 'ex ante'), while those ensuring dynamic flexibility are classified as organizational–managerial ones.

Flexibility obtained with FMS has remarkable limits, as it is obtained assuming a constant amount of information and absence of learning processes. One of the first authors to express this limit was Schonberger (1986) who, with the term 'frugal automation', intended to stress that flexibility was not so much the ability to produce a high number of different codes as the ability to pass from an efficient type of production to another equally efficient one by making organizational–managerial choices which require lower investments in terms of fixed assets (thus the definition 'frugal automation').

More importance is therefore given to dynamic flexibility, obtained by using less sophisticated machines which leave more space for the enterprise to fully exploit the learning process on products and processes, and follow new paths when unexpected market needs turn up.

The greater potentiality to change due to the firm's increased degrees of freedom relative to decisions, obtained thanks to the increased knowledge of the internal and external situation, lead to the consideration of flexibility as a competitive priority or key success factor.

The importance of a dynamic production (and therefore of dynamic flexibility) given by learning processes (organizational–managerial choices) is underlined by authors such as Hayes *et al.* (1988) who brilliantly synthesize the concept of dynamics in relation to learning processes, in the title of their famous book: 'Dynamic Manufacturing—Creating the Learning Organization'.

The operational choices (both technological and organizational–managerial ones) concern both the environment outside and within the enterprise. This recalls both the so-called vertical classification of flexibility, articulated at resource, function, firm and network level (Gerwin 1987, Mair 1994), and the horizontal one, articulated according to the pattern of the operational value chain, with actions on supplying, design, manufacturing and distribution (Kim 1991).

The internal actions on the design and manufacturing phases aimed at ensuring flexibility may follow traditional routes such as design/manufacturing overcapacities and over-supplies (Newman *et al.* 1993), or more innovative ones, such as the implementation of Just-In-Time, Concurrent Engineering and Total Quality Management programmes.

As regards flexibility determinants, these are relative to variables such as the growing uncertainty of the demand, the increasingly shorter life-cycles of products and technologies, the increasingly wider range of products, increasingly marked product customization, increasingly shorter delivery times. Therefore flexibility, seen as performance, may be required in relation to variables such as production volumes, mix, introduction of new products, etc., as seen when analysing the classification of flexibility per object of the variation; this requires an analysis of the trade-offs between performances when choosing configuration and functioning of the manufacturing system.

A fundamental subject like the measurement of flexibility still offers the opportunity for further research. In fact, certain operationalizations for measuring the levels of flexibility are still not widely accepted: direct indicators, indirect ones (such as those which consider the values of the determinants of flexibility), and synthetic ones.

In conclusion, the analysis of the literature shows an articulated and complex frame, with certain questions still open, which require a future effort both of theoretical (to formulate unitary concepts) and empirical (aimed at testing the numerous theses presented) research.

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