

A MODEL FOR MEASURING MANUFACTURING FLEXIBILITY

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ABSTRACT

In this paper the authors suggest a model for measuring manufacturing flexibility, as from the classification of flexibility based on the objects of variation and related to the characteristics of this variation. As a consequence, there are nine classes of flexibility, and the most frequent types of flexibility of literature take their place inside this frame. At least an indicator for each of the nine classes/types of flexibility is so operationalized, allowing both to value a synthetic flexibility (aggregating by weights the levels in each flexibility) and to draw up a benchmark among different plants with reference to single classes of flexibility. Finally, the outcomes related to flexibility have been compared with plant efficiency, in order to examine possible degrees of trade-off between flexibility and efficiency. The proposed model has been tested in five different plants.

Keywords: Manufacturing Flexibility, Flexibility Measurement, Flexibility/Efficiency Trade-off

RESEARCH STREAMS ON MANUFACTURING FLEXIBILITY

Literature on manufacturing flexibility has been widely developed and can be articulated in six main streams (De Toni e Tonchia, 1998): 1) definitions of flexibility (characteristic of the interface between a system and its external environment, capability of adaptation/change etc.), 2) analysis of the factors which cause the demand for flexibility (demand variability, internal uncertainty etc.), 3) classification/dimensions of flexibility as a performance, 4) its measurement (indicators), 5) analysis of the choices/levers leading to flexibility (technological and organizational/managerial ones), 6) ways of understanding manufacturing flexibility (either with strategic or operational aim, defensive or offensive value, directed in achieving other performances etc.).

Particularly, manufacturing flexibility can be classified in accordance with different logics: 1) horizontal (or by stages), distinguishing between internal phases and value chain boundaries; 2) vertical (or hierarchical), starting from single resource flexibilities to an overall flexibility; 3) temporal, that is in the short or long period; 4) by the object of variation (volume, mix, features of the products or of the productive processes etc.); 5) mixed (i.e. in accordance with more preceding variables).

For each of these logics many kinds of flexibility have been proposed, starting with the historical contributes of Zelenovich (1982), Slack (1983), Brown et al. (1984),

Mandelbaum and Buzacott (1986), Gerwin (1987) to the most recent ones, such as - for example - Koste and Malhotra (1999), and D'Souza and Williams (2000), but without changing the main types of flexibility: of volume, mix, cycle, product, process, etc.

MEASUREMENT OF MANUFACTURING FLEXIBILITY

Compared with the importance and steady interest that flexibility arouse both in academic and in managerial field, measurement of flexibility is still anything but a developed subject, both for the various aspects that characterize flexibility and the lack of indicators that can directly measure it. Measurement of flexibility is one of the research streams on flexibility, probably the less concretely developed one.

In the majority of cases, the measurement of flexibility, developed by dimensions, takes place by Likert-type scales: respondents are asked to assess various manufacturing flexibilities by the extent of their agreement or disagreement on flexibility performance results and/or flexibility programs i.e. in both cases in a personal subjective way. For example, Zang et al. (2003) consider "flexible manufacturing competencies" (machine, labor, material handling, and routing flexibilities) which have impact on "flexible manufacturing capabilities" (volume, and mix flexibilities), these latter having impact on customer satisfaction. Chang et al. (2003) link six measured flexibility dimensions (new product, product mix, volume, delivery, modification, service flexibilities) to business performances according to three different business strategies.

But in both cases the measurement of the aforementioned flexibilities does *not* take place in an objective way, that is, linking the several dimensions of flexibility with objective numerical indicators.

One of few cases where flexibility is measured with objective numerical values and not with scale values is that presented by Pagell e Krause (1999), but the construction of an overall indicator of "operational flexibility" takes place using *only* four indicators, adding their related standardized values: number of distinct parts or product families made in the plant, average batch size for the plant, new parts or products (as a percent of existing ones) introduced in a year, parts or products (as a percent of existing ones) retired in a year.

A MODEL FOR MEASURING MANUFACTURING FLEXIBILITY

The authors present here a model for measuring manufacturing flexibility, as from the classification of flexibilities based on the *objects* of variation and the *characteristics* of the relative variation.

The objects of variation

As far as concerning the *objects of variation*, the model considers:

- the *productive volume*;
- the *product characteristics*;
- the *production process characteristics*.

The characteristics of variation

Concerning the *characteristics of variation*, the model considers (also see Barad and Sipper, 1988):

- the *state conditions* (or starting conditions);
- the *kind of transition* (short-term, generally reversible; long-term, usually not

reversible).

For the three different “objects of variation”, the use of variables “state conditions” and “kind of transition” (reversible and irreversible) enable to sketch out the joint classification of manufacturing flexibilities as proposed in Table 1.

Table 1 – Classes of manufacturing flexibility

		OBJECT OF THE VARIATION	VOLUME	PRODUCT	PROCESS
		HORIZON			
STATIC FLEX	Now (state conditions)	Productive capacity ①	Product range width & depth ②	Productive phases width ③	
	Short term (reversible transitions)	Volume flexibility ④	Mix flexibility ⑤	Cycle flexibility ⑥	
DYNAMIC FLEXIBILITIES	Long term (irreversible transitions)	Expansion flexibility ⑦	Product flexibility ⑧	Technology flexibility ⑨	

Classes of manufacturing flexibility

As a consequence, there are nine classes of flexibility, and the most frequent types of flexibility found in literature take their place inside them (for a complete review of definitions, see: Sethi and Sethi, 1990, De Toni and Tonchia, 1998).

Flexibility has been often considered only under the point of view of a time performance; strictly speaking, flexibility must be interpreted as the *capacity to change something* not only quickly but at low costs and without a worsening in quality too (Upton, 1995). Using a mathematical function (at the partial derivatives), we could write:

$$\text{Flexibility} = \frac{\partial^3 O}{\partial T \partial C \partial Q}$$

where “O” is a measure of the object which varies (e.g. the production volume), T, C, and Q respectively a time, cost, and quality performance.

Nevertheless, since the variations both of costs (rises) and quality (declines) should be much lower than those of the times, at stake in order to allow to speak about real flexibility, the latter is often compared to a time performance i.e. it is considered the sole variation of time as the denominator:

Flexibility = $d O / d T$.

Therefore, if we assume flexibility to be the “capacity of variation in time of a certain object”, then it is possible to affirm that - in formal terms - it is not correct to consider as flexibility the three static flexibilities of Table 1, i.e. on the level of *productive capacity*, *product range width & depth*, and *productive phases width*.

These three state conditions often represent an indirect mark of flexibility yet, and for this reason are considered in our model.

As far as concerning the feature “kind of transition” (either reversible or not), it enables us to differentiate *volume flexibility* (generally considered on short term for floating and reversible variations of demand, and as a consequence for the quantity of production) from *expansion flexibility* (considered on long term for irreversible variations of quantity to produce). Likewise, *mix flexibility* must be considered on short term with relation to reversible floating of output’s composition, while *product flexibility* is considered for variations of output’s composition on long term (product specifications’ change). Similarly, *cycles flexibility* displays features of reversibility, while *technology flexibility* introduces non reversible changes in modes of production.

THE TEST OF THE MODEL

Company and plants

The proposed model has been tested in 5 different plants of Finmek S.p.A. Group, which is the second European giant concerning Electronic Manufacturing Services (EMS), owning nearly 600 M Euro and 2.300 employees.

With the word EMS we refer to the production and assembly of electronic components by “contract” on demand from Original Equipment Manufacturers (OEM). These ones are the original producers of the electronic appliance and hold its trademark; they are the great ones of the Information & Communication Technologies (customers of Finmek are, among the others: Alcatel, Ericsson, Motorola, Nokia, Siemens, IBM, HP, Apple, Philips), that - as time went by - have undertaken a process of outsourcing of production activities, which has led indeed to the birth and continuous development of EMS.

Managing a total of 11 production plants all around the world and coordinating a wide network of subcontractors, in a strongly dynamic context, the Company has heavily felt the necessity of measuring and keeping under control the flexibility of its production plants.

Types and indicators of flexibility

At least an indicator for each of the nine classes/types of flexibility of Table 1 has been operationalized. These numerical and precise indicators allowed both to value a synthetic flexibility for each plant (aggregating by weights the levels of the several flexibilities), and to draw up a benchmark among the plants with reference to single classes of flexibility.

Eight - among the nine dimensions of flexibility - have been studied in order to identify the most appropriate indicators of performance. *Cycle flexibility* hasn’t been studied, as the technology it has been considered (SMT - Surface Mount Technology) has fixed production cycles. The indicators that have been pointed out have been the following ones (Table 2):

1. for *productivity capacity* (that is, the state condition with volumes as object), the number of components that can be assembled each hour by SMT lines at disposal;
2. for *width & depth of product range* (that is, the state condition with products as object), respectively the number of families of products carried out and the average (or total) number of items assembled within a family. Finmek's products have been subdivided into six families: 1. parts for home appliances; 2. parts "consumer"; 3. parts for office appliances; 4. parts for telecommunication systems; 5. parts for mobile phones; 6. parts for the automotive sector. To give an example, in the plant in Avezzano, parts for mobile phones (1 code), parts for home appliances (4 codes), parts for telecommunication systems (35 codes) and parts for the automotive sector (38 codes) are assembled; as a consequence, the product range width is 4 and the product range depth is 78;
3. for *productive phases width* (that is, the state condition with productive processes as object), the number of productive processes that can be carried out by single plants, according to owned equipment. The three manufacturing technologies used nowadays are the following: 1. SMT "reflow" assembling; 2. SMT "glue" assembling; 3. PTH ("Pin-Through-Hole") assembling. Productive cycles originate from the combination of these; particularly, those carried out by Finmek are: 1. SMT reflow; 2. SMT reflow + SMT glue; 3. SMT reflow + SMT glue + PTH; 4. PTH. The several plants carry out one or more of these four cycles: Avezzano, three; Aversa and Marcianise, two; etc.;

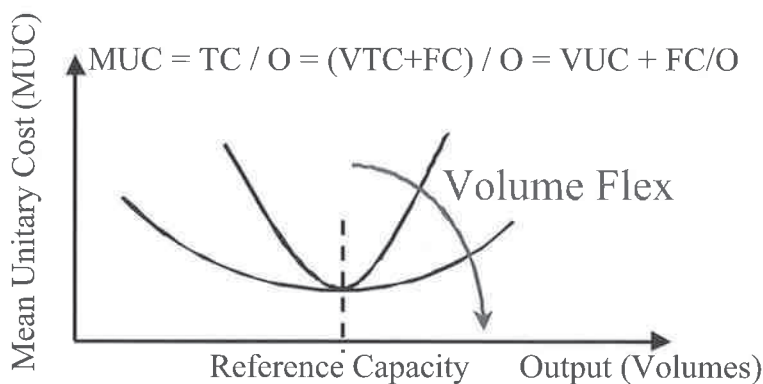


Figure 1 – Volume flexibility = $d(MUC) / d(O)$

[TC = Total Costs; VTC = Variable Total Costs; VUC = Variable Unitary Costs;
FC = Fix Costs; O = Output]

4. for *volume flexibility* (that is, short term reversible transition concerning volumes), the derivative of the curve of mean unitary cost. With reference to productive volumes indeed, it can be considered the curve of mean unitary cost, the latter being defined as the ratio between total cost (addition of fixed and variable costs) and productive volume (output): the flatter is this curve, the greater is the flexibility, that is the variation of costs is low if compared with the variation of volumes (Figure 1). While FC are - by definition - fixed in respect to volumes, VUC can be a function of volumes.
5. for *mix flexibility* (that is, short term reversible transition concerning products), the

- average set-up time of SMT lines, that is in how much time it is possible to modify the typology of assembled products;
6. for *expansion flexibility* (that is, for medium-long term irreversible transition concerning volumes), costs to assume for the increase of turns and/or working days per week (compared with the proportional increase in productive capacity). On the contrary, the possibility to activate new SMT lines - besides investments - is linked with the availability of room in the existing buildings, and therefore it is not considered here as a performance;
 7. for *product flexibility* (that is, for medium-long term irreversible transition concerning products), the number and type of parts introduced in the last year, and the costs and times of these introductions. For example, the plant in Avezzano has been the most flexible, with the introduction of 63 new parts (SMT "reflow" process) among 100 produced;
 8. for *technology flexibility* (that is, for medium-long term irreversible transition concerning productive processes), the investments in new equipment undertaken for a plant in order to introduce new process phases.

Table 2 – Flexibility types and relative indicators in Finmek S.p.A.

	Types of flexibility	Indicators of flexibility
Static flexi- bility	productivity capacity	number of components that can be assembled each hour by the lines
	width & depth of product range	number of product families & sum of items for each family
	productive phases width	number of productive processes that can be carried out
Dynamic flexibility (short term)	volume flexibility	derivative of mean unitary cost's curve as to productive volume
	mix flexibility	average set-up time of the productive lines
	cycle flexibility	[not pertaining]
Dynamic flexibility (long term)	expansion flexibility	costs compared with the proportional increase in productive capacity
	product flexibility	no., types, costs and times for the introduction of new parts in a year
	technology flexibility	technical investments for the introduction of new process phases

The abovementioned flexibility indicators have been applied to five plants, moreover the most complex and relevant of the Finmek group: Aversa (CE), Avezzano (AQ), Marcianise (CE), Ronchi dei Legionari (GO) in Italy and Berlin in Germany. Comparing the related values, the evaluations of Figure 2 have been attained; they summarize the numerical values noticed, simply distinguishing - in this first stage of method's application - into a high ("H") or low degree of flexibility ("L").

Classes of flexibility			Plant - Aversa			Plant - Berlin		
Productive capacity	Product range	Phases width	L	L	L	L	L	L
Volume	Mix	Productive cycles	L	H		H	L	
Expansion	Product	Technology	L	L	H	L	H	L

Plant - Ronchi			Plant - Marcianise			Plant - Avezzano		
H	L	L	H	H	H	H	H	H
H	L		L	H		H	H	
H	H	L	H	H	H	H	H	H

Figure 2 – Plant benchmark on flexibility (H = High; L = Low)

The outcomes related to flexibility have been compared with plant productive efficiency too, in order to value possible degrees of *trade-off* between flexibility and efficiency. Efficiency has been defined as the ratio between produced cards (pieces) and consumed man-hours. With the exception of Berlin - which is a plant provided with rather obsolete equipments and with a lower working productivity - it could be inferred how flexibility proves still to be in trade-off with efficiency (Figure 3): particularly, the plants in Avezzano and Marcianise, characterized by a greater productive complexity, have had to be equipped with flexible machinery to manage it, but this has led to a loss as far as efficiency.

CONCLUSIONS

The complex and articulate concept of flexibility of productive systems can be analysed and the related performance can be evaluated only by resolving flexibility itself into *dimensions*.

First of all we have to distinguish between dimensions that have to be enrolled into a *state flexibility* (or “range”) and those that have to be enrolled into a *dynamic flexibility* (or “response”).

Successively, considering the objects of “variation” linked with manufacturing flexibility (that is, *volumes*, *products*, and *processes*), and distinguishing the aforementioned dynamic flexibility between “short-term” (*reversible*) and “long-term” (*irreversible*), a classification of flexibility into different classes (nine ones in Table 1) can be obtained.