Flexibility

A literature review

General Definitions:

Due to the multi-dimensional nature of flexibility and the various views of flexibility which result: flexibility has been viewed and studied as a physical property, an attribute of decision making, an economic indicator, and a strategic tool. At least 50 terms exists for various types of flexibilities.

- Flexibility, to be employed in realistic manner, should result in little penalty in time, effort, cost or performance.
- Flexibility is yielding the best possible performance in the face of environmental variability. Technology flexibility is the ability to adapt to both incremental and revolutionary change in the business or business process with minimal penalty to current time, effort, cost, or performance.
- The notion of flexibility as a tentative to quantitatively describe the functional richness that the system under design is able to implement.
- Flexibility is defined in manufacturing system literature as the ability of the system to adapt itself to the various changes (Zelenovic, 1982).
- Flexibility as characteristic of the interface between a system and its external environment (Correa 1994). In this case, flexibility acts as a filter, buffering the system from external perturbations. Flexibility thus functions as an absorber for uncertainty. The external perturbations are characterized by: measure, frequency, novelty and certainty.
- Flexibility 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.
- In behavioral psychology, flexibility is defined as degree of response variability found in an organism. Response variability is defined the degree of diversity in reactions shown by a particular person under normal, everyday condition which are the type of conditions under which incremental change occurs. The other dimension of flexibility is the responsiveness to the environmental pressure to change.

Request for Flexibility

- 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.

Some Flexibility related definitions

- Adaptability characterizes revolutionary changes in the business process environment. It is system's ability to conform to new production technologies and manufacturing new products.
- Adaptation is the optimization of a particular niche or business process.
- Reconfigurability: add or subtract capacity.
- Uncertainty can be informative (a lack of information) and of knowledge (subjective limits of those who take decisions).
- Time intervenes in terms of sequentiality (concept of irreversibility of decisions) and cumulativeness (the accumulation of knowledge which can improve decision-making performances).

Major Flexibility Types

- Major flexibility types defined for manufacturing systems (Falkner, 1986)
  - Process: The ability to produce a set of products
  - Product: The ability to change to process a new product
  - Routing: The ability to process a given set of products on alternative machines
  - Volume: The ability to profitably operate on varying demand levels
  - Expansion: The ability to add more capacity
  - Production: the whole set of product types that can be processed

- Sethi and Sethi (1990), after having considered eleven types of flexibility based on the object of variation articulate them on three levels:
  - Component or basic flexibilities (machine, material handling, and operation flexibility)
  - System flexibilities (process, routing, product, volume, and expansion flexibility)
  - Aggregate flexibilities (program flexibility, deriving from the process, and routing 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*

- Process flexibility: the ability of people to make changes to the technology using management processes that support business process changes.
  Determinants of process flexibility:
    - Rate of response: The degree to which changes can be made to a technology in a timely manner.
    - Expertise: The degree to which up-to-date knowledge about the operation and maintenance of a technology exists and is communicated.
    - Coordination of action: The degree to which the technology maintenance and user organizations operate according to the requirements of each other and the total organization.

- Structural flexibility: is the capability of the design and organization of a technology to be successfully adapted to business process changes.
  Determinants of structural flexibility:
    - Modularity: the degree of formal design separation within a technology application. It can provide manageable units of programs or hardware that can be modified.
    - Change acceptance: The acceptance of pressure to change is one of the indicators of the psychological responsiveness to the environment. The magnitude of aftereffects of change is an indicator of coping ability. It is defined as the degree to which a technology contains built-in capacity for change.
    - Consistency: the degree to which data and components are integrated consistently across a technology.

- In strategic organizational flexibility is based on two dimensions: ex ante (anticipates change before it happens, agility and versatility are its characteristics-reflect a built in capacity to anticipate and deal with change) and ex post (incremental in nature).

- *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-program;
  - 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. ;
- *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
- *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 a*l. (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-u*p, the *product mi*x, and the *part processe*d, respectively
- *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
- *Routing* 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 routing flexibility: the part may be processed in a routing 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 routings are fixed, and only in the case of failures are the alternative ones used; (b) effective-the same part is processed with different routings, independently of failures
- *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
- *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

- *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.
- 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).

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

  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);

  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 *labor* flexibility),

  (b) *Mix* flexibility *(short-ter*m, *medium-ter*m, and *long-term* flexibility),

  (c) *Volume* flexibility,

  (d) *Layout* flexibility,

  (e) *Component* flexibility.

- *Machine flexibility* deals with the ease of making changes among the operations required to produce a number of products. It is measured by the number of operations that a workstation performs and the time needed to switch from one operation to another.

- *Routing flexibility* is the ability of a production system to manufacture a part using several alternative routes in the system and it is determined by the number of such potential routes and back-up machinery in case of breakdowns.
- *Material Handling System flexibility* is the ability of a transportation system to move efficiently several part-types from one point to another. It can be measured by the number, diversity, and transportation time of work pieces.
- *Product flexibility* is the ease with which the part mix can be changed in order to manufacture or assemble new products. Quantitatively it is measured by the time or the cost needed to switch from one part mix to another.
- *Operation flexibility* of a part refers to the ease of changing the sequence of the operations required to manufacture this part and it can be measured by the number of different operation sequences the part may be produced.
- *Process flexibility* measures the ability of a manufacturing system to produce several part-types without reconfigurations. An index of this flexibility is the number of part-types that can be simultaneously processed by the system.
- *Volume flexibility* is the ability of a system to operate profitably at different throughput levels. It is quantified by the range of volumes at which the system runs profitably.
- *Expansion flexibility* refers to a system's capability to be modular and expandable. It can be measured by the time or cost required for the system's expansion to a given capacity.
- *Labor flexibility* is the ease of moving personnel to different departments of an organization and it is achieved by the aptitude of multi-trained staff to carry out a wide variety of tasks.

Specifications of Flexibility metric

Any practical flexibility metric should work as follows:

1. Focus on specific flexibility types from which overall flexibility measures will be derived. The observable parameters for each measure should be specified together with the derivation methodology.
2. Allow flexibility comparisons among different installations.
3. Provide a situation specific measurement by taking into account the particular characteristics of the system.
4. Incorporate the accumulated human knowledge.

Measures and Models of Flexibility

- Webster (1980): As the annual material handling cost

- Zelenovic (1982):
  - Design adequacy: probability that the current system structure will adapt itself to the environmental changes and manufacturing needs within the current design limits
  - Adaption flexibility: The time required for the system transformation form one job to another.

- Kumar (1986): Entropy based measure of loading flexibility which represents the possibility of regulating the product visits to the various work centers in the system. The measure is based on markovian analysis of the interrelationship between machines in the manufacturing system.

$$F = -\sum_{i=1}^{n} q_i \ln q_i$$

q_i is the probability of a product going to visit next machine i, and n is the number of machines in the system.

- Yao (1985): Another entropy based flexibility. for each possible product routing, an entropy is computed as the overall reliability of machines required for such routing. machine reliability is defined as the expected percentage of time a machine is operational.

- Son and Park (1987):
  - Equipment flexibility F_E: the capacity of equipment to accommodate new products.
  - Product flexibility F_P: The adaptability of the system to changes in product mix.
  - Process flexibility: The adaptability to various changes in process such as machine breakdowns and disturbances in product schedules.
  - Demand flexibility: The adaptability to changes in demand rate

$$F_E = \frac{O_T}{C_L}$$

$$F_S = \frac{O_T}{C_W}$$

$$F_P = \frac{O_T}{C_A}$$

$$F_D = \frac{O_T}{C_H}$$

Where

O_T= System output
C_A= Machine setting cost
C_H= Cost of raw material and finished products inventories
C_L= Machine idle time cost
C_W= Cost of job waiting time

- Brill and Madelbaum (1989): flexibility measure based on the division of the activities performed by the system into task τ_i assigning a weight to each task $W(\tau_i)$ and determining a machine task efficiency rating $e(M,\tau_i)$. Flexibility of machine M relative to a set of tasks T is compute as follows:

$$F_{M,T} = \frac{\sum_{\tau \in T} e(M,\tau) W(\tau)}{\sum_{\tau \in T} W(\tau)}$$

- Taymaz (1989): Classification of the flexibility according to term length. short-term and long-term

Classification of the Flexibilities

- Horizontal or by phases;
  Vertical or hierarchical;
  Temporal;
  By the object of the variation.

- 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 center 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 centers);
- Long-term flexibility (the possibility to adapt the system to new types of products or mix of components).

- 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 *material*s, 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 and 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 a*l. 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 *changeover*, 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-routing flexibility'), measured by the number of possible routing 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).

- Zhao (1998) proposed two related software flexibility concepts: system adaptability and system versatility.

  System adaptability is the capability to modify the system to cope with major changes in business processes with little or no interruption to business operations.

  System versatility (or system robustness) is the capability of the system to allow flexible procedures to deal with exceptions in processes and procedures.

- Deiters, Goesmann, and Löffeler (2000) dealt with the issue of flexibility in technical, organizational, and human perspectives. They classify flexibility into four dimensions: *process flexibility*, *inter-organizational flexibility*, *flexible management and knowledge*, and *flexible task allocation*. They further proposed conceptual solutions for achieving flexible workflow support.

- 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.