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MANUFACTURING FLEXIBILITY: CHARACTERIZATION & MEASUREMENT

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ABSTRACT

Flexibility has been recognized as a key competitive advantage for any manufacturing firm. It is particularly important in current manufacturing environment with growing dominance of high mix and low volume production. The characterization and measurement of the flexibility is the focus of this paper. The goal is to enable manufacturing professionals to plan, monitor and mange the flexibility of their manufacturing resources, particularly in situation when response is critical, the future demands are difficult to forecast and error tolerance is relatively small.

To accomplish these goal initial attempts were made to understand the notion behind the flexibility. This paper presents the viewpoint that flexibility being intrinsic in nature of a manufacturing system; we try to measure the flexibility independently. The efforts have been made to characterize flexibility in the form of four flexibility namely: capacity range, capacity response, capability range and capability response. Based on the flexibility characterization an approach to the measurement of flexibility at a given system level is defined. The critical aspect is to identify the distinct capability regions based on critical capability drivers and to model the relationship of capacity among the regions.

Keywords: *flexibility, flexibility characterization, capability range, capacity range, capability response, capacity response*

INTRODUCTION

Manufacturing has gone through successive periods of changes from the agrarian age to the industrial age to the information change. The inherent assumption to characterize mass production systems are the predictability and constancy of customer demand. The basic characteristics of such factories include high volume production, long production runs, dedicated machines, less product variety, lower marginal cost, higher inventories and make to stock production. Moreover, as product variety increases and batch size decreases, opportunities for economies of scale fade.

After the 1980's, companies faced the following market characteristics:

- Reduction of product life cycle
- Increased product variation
- Complicated consumer demands
- Vigorous competition

The main reason behind the shift in market characteristics, from stability & predictability to the above mentioned characteristics, is the increased customer expectations. Customers want their product customized in terms of mix and volume and also want them delivered in shorter lead time with lower price. These increased customer expectations have induced a lot of uncertainties in the current manufacturing environment.

In the past decade, There were a lot of advantages and innovations in production technology. These technologies facilitates companies to produce a wide variety of products with very little setup effort. The new flexible technology facilitates the production of a variety of products at the same rate, which had only been possible with mass production but for a few products or a single product. The strict one to one relationship between products and processes is no longer viable.

Most manufacturing companies need to adapt to these new technologies as they represent the effective solutions of an unresolved problem or if the companies do not adopt than they might lose competitive power. Market changes & technological revolution are connected with and effect each other. Technological development follows on market change and tries to meet market's new demands, while in turn, it also creates new customer demands, Meaning that technology sometimes generates new market.

The current manufacturing environment in which companies have to operate is extremely turbulent. Uncertainties not only in terms of the right components or sub- assembly delivery at the right time, but also within the manufacturing systems e.g. worker absenteesm, machine failure, these condition leads to a situation of limited stability and predictability. Due to above factors, the challenges posed is to manage resources capabilities and capabilities in order to overcome uncertainties imposed by changes in the operating environment.

As mentioned before, changes in the operating environment, increased customer expectations, and technological innovations create uncertainties in a manufacturing environment. It is virtually impossible to eliminate all uncertainties from the production environment. Although it may be possible to reduce the uncertainties related to the supply market, there is a tendency that, in future, consumer market will demand an increasing variability of the products with shorter life cycles. The widely quoted traditional way overcome uncertainties is to have buffer inventory.

This method is no longer viable to deal with the uncertainties related to changes in customer requirement specifically, with respect to product mix and volume. Inventory provides a safety cushion only for a narrow segment of demand uncertainty. If the product mix is uncertain, accumulating an inventory of every product will leave manufacturer with inventory of unwanted products and changes in technology can leave manufacturer with stocks of obsolete inventory. Additionally, the impact of over spending capital on inventory would lead to lower investment. in the area such as research & development, marketing etc. Based on the above, it is clear that traditional method of keeping inventory may not provide much help in resolving uncertainties imposed by the dynamic manufacturing environment. The most effective way to buffer the uncertainties is to introduce flexibility into the system.

In the current manufacturing environment with growing dominance of high mix and low volume production, increased customer expectations along with the prevailing uncertainties. Flexibility has emerged as an important method to achieve competitive advantage. There is yet no consensus on how flexibility should be characterized, analyzes and measured. It is vague and difficult yet critical to competitiveness. One of the main difficulties in the development of objective measures of flexibility is its characteristics of being a potential and its inherent multidimensionality. The major obstacle in developing absolute measure of flexibility. Without appropriate flexibility measures it is very difficult to systematically analyse and enhance the flexibility of manufacturing system. This is why manufacturing industry finds it difficult to incorporate flexibility as a tool in dealing with the high variety and low volume production environment. The ongoing discussion is far from being characterized, consequently meaningful measure, comparison and validation of flexibility are still a popular topic of research.

The implications of characterizing flexibility measurement are significant for manufacturing companies in the area of capacity planning. Capacity planning performed by MRP- II inherently assumes that all the resources are either completely different or identical. However, machines often have overlapping capabilities & varying efficiencies. Hence the characterization and measurement of flexibility at various system levels help companies to identify the inherent and required potential in better way, thereby, facilitating in enhancing accuracy of capacity planning.

This paper tries to develop a systematic approach to characterize, and measure manufacturing flexibility. Specifically the methodology to analyze and measure flexibility for high variety and low volume production. Ultimate goal is to enable manufacturing companies to monitor and manage flexibility of their resources.

DECOUPLING FLEXIBILITY FROM CHANGES IN OPERATING ENVIRONMENT & FROM THE PERFORMNACE CRITERION

Traditionally there exists two ways of defining flexibility. The first one links flexibility with the changes in operating environment, measures based on these definitions are relative measures to develop measures that are absolute and comparable between different enterprises and branches. This needs to be analyzes separately which allows using absolute flexibility measures. As Shown in figure below here we distinguish two types of flexibility required flexibility and inherent flexibility. The required flexibility is determined by the changes in operating environment, the manufacturing strategy and performance criteria. The inherent flexibility is determined by the potential of the technological resources and worker by organizational decision. Henceforth the flexibility of the system refers to the inherent flexibility. The implications of proposed decoupling are that flexibility can be described irrespective of the changes in the operating environment. The comparison of the required and inherent flexibility helps to determine whether a system has the right type and amount of flexibility. One might think of cases in which the inherent flexibility is high but does not match with the required flexibility; than the system does not have right kind of flexibility.

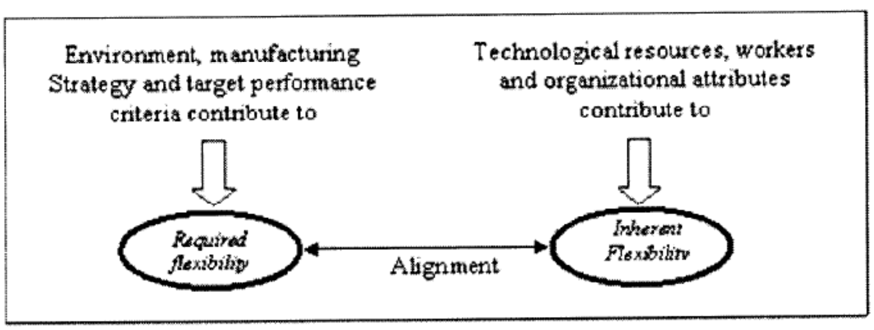


Figure 1:

One way of defining flexibility concept is linking it with the changes in operating environment as well as with performance measures. This makes it even more difficult to develop flexibility measures. Though the purpose of flexibility is to contribute to words the performance as emphasized in the definitions, flexibility is not the only factor contributing to a system performance as shown in figure.

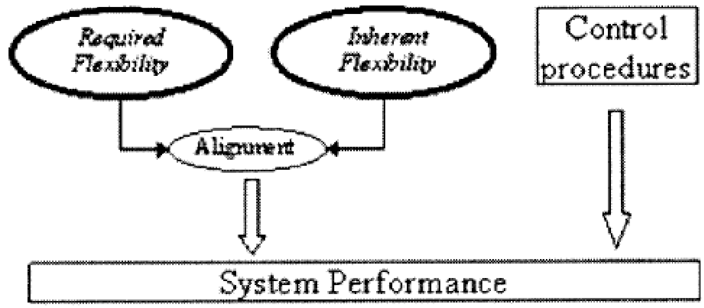


Figure -2 Decoupling Flexibility From Performance Criterion

An improper alignment between the required and the potential flexibility as well as inadequate control procedures can be responsible for the manufacturing system performance. Control procedures use the inherent flexibility available in the system. This poor performance not always is a reflection of insufficient or wrong flexibility. With this view, performance criteria are only a suitable measure for flexibility if the required flexibility and the control procedures are the same in all the systems compared. In that case, the only differentiator in the system's performance, while making comparison is inherent flexibility.

Approach To Flexibility Characterization: The proposed decoupling facilitates treating flexibility as an inherent property of the system under consideration with this understanding the intrinsic properties of the production systems are extracted in order to characterize flexibility. To accomplish this we propose the following three aspects for flexibility characterization.

Elements: We define flexibility as the ability to change. The word ability here refers to the potential of the system under consideration. In other words flexibility is not a demonstrated quality. The volume flexibility is mainly concerned with the magnitude of change while mix flexibility is concerned with the change in the type of mix. Capability and capacity are the elements providing the system on ability to change from the mix and from the magnitude perspective respectively.

Time Horizon: Capacity and capability are the enablers for the potential of a system in consideration. However, they are subject to changes which are considered by given time horizon. In the longer term, means to enhance the capacity and the capability are different then the means available in the shorter terms.

Dimensions: Flexibility is a multidimensional concept. Since capacity and capability provide an ability top change, this change can be in two dimensions- Range and Response. In other words both capacity and capability can change in terms of range and response. Based on this understanding we try to characterize four descriptors of flexibility in terms of Volume and mix flexibility.

- Capability Range
- Capability response
- Capacity Range
- Capacity Response

FLEXIBILITY DESCRIPTORS: The proposed four flexibility descriptors are capable of capturing and representing the flexibility at various system levels in a simple yet effective ways. The details of these descriptors re outlined below:

CAPABILITY RANGE & CAPABILITY RESPONSE: The number of capability attributes of any system under consideration is so great that it is not viable to consider each attribute for flexibility characterization. Hence to make it practical enough the focus should be on critical capability attributes. The desired level of accuracy plays an important role in determining the capability attribute. It is always possible to define capability range and capability response for each capability attributes. The critical capability attributes related to capability range & capability response may be different.

Capability Range: It deposits the application domain of the system under consideration. This domain is characterized in terms of the critical driver. The notation & representation of this descriptor is different at different system levels. In general, if J_{CBRA} represents a set, consisting of 'p' critical capability drivers then at the machine level the capability range can be represented by following super set

$CBRA_{machine} = \{A_1, A_2, A_3\text{----------}A_P\}$

Where $A_j = \{ X/ X \in VCD_j\}$

VCD_j = set of values assumed by critical driver j = $j \in J_{CBRA}$

The set VCD_j may consist of values within a continuous domain or a discrete domain. Normally for a single machine, single driver is sufficient to characterize the capability range. At the work system level, which consists of parallel machines, critical drivers are identified in terms of technical system constraints. Usually it will be possible to identify technical system constraints responsible for this. In some cases it might be the working space that determine the size of a product that can be processes by machine or in other case it may refer to processing parameters. In general if J_{CBRA} represents a set of critical capability drivers 'M' represents the set of given machines and VCD_{mj} represents the set of values assumed by machine 'm' corresponding to driver 'j', then the capability range of work system for a given capability driver 'j' is given by

$$VCD_{.j}^{ws}\ ws = \bigcup_{m \in M} .VCDj\ \forall j\ \in JCBRA$$

The range of work system for a given driver is derived based on the union operation of capability ranges of workstations in a given work system. In case we have ‘p’ capability drivers the capability range of whole work system against will be superset represented by

$$CBRA\ ws = \{ A_1^{ws}, A_2^{ws}, A_3^{ws}, \text{----------------} A_p^{ws}\}$$

$$\text{Whereas } Aj^{ws} = \{ X/ X \in VCD_j^{ws}\}$$

Similar to above representation, the capability range of a cell, consisting of ‘g’ work system will be a superset of capability range of various work system given by

$$CBRA_{cell} = \{CBRA_{ws}^{1}, CBRA_{ws}^{2}, CBRA_{ws}^{3}, \text{-------} CBRA_{ws}^{g}\}$$

CAPABILITY RESPONSE: this descriptor indicated the effort required to switch from one specific state with in capability range to another state within the capability range. The classic measure for capability response is setup time or cost. Since, cost involves many intangibles that are difficult to quantify, in our discussion we consider set up time as the measure of capability response. The lower the capability response is, the easier it is to deal with a high product variety.

As mentioned earlier for each capability attributes it is always possible to define both capability range and capability response. However, there are cases, in which setup time is zero for critical attributes of capacity range. In this case the attribute is only critical for capability range. And there are cases where the setup time is non zero for non critical attributes of capability range. In this case the attributes is only critical for capability response.

CAPACITY RANGE & CAPACITY RESPONSE: The capacity of the system in consideration can be measured in any convenient unit i.e. standard working hours (swh) or parts per unit time. In most of the cases the production system produce varied product mix. One needs to find a common standard/ unit of measure to be able to define capacity properly. This avoids a plethora of resources. The capacity of all resources, including resources with different capability and efficiencies is measured in standard working hours as a common unit. Moreover capacity is not a single number but it is distributed over the capability range which may or may not be uniform.

CAPACITY RANGE: This descriptor indicates the range in which capacity of a system can vary. It is the only descriptor which is linked with the magnitude. The capacity of the system can vary due to many factors. These factors can be classified based on the time duration, namely short term sources and long term sources. The major short term sources that facilitates varying the capacity of the systems are:

Overtime: In most of the industries, it is difficult to forecast accurately and there exists variability in aggregate volume requirements. Especially during the peak seasons the variation in demand are quite high. In addition volume to the variation in demand, in few of the companies, rework is also an issue. To meet the deadlines promised to customers, companies usually introduce overtime to compensate the rework or increase in aggreagate demand. The amount of overtime is dependent on the company policies and also its constrained by the rules on overtime is dependent on the company policies and also its constrained by the rules and regulation of central/ state government.

Additional Shift: In few of the companies the additional shift is introduced to overcome the demand fluctuations. It depends on the company policy in few of the cases companies work on one shift and the second shift is mainly used to operate high use manufacturing equipment. The second shift could be full staffed to increase the capacity of the plant. In some other cases companies introduce additional shift on other weekends to overcome the surge in demand.

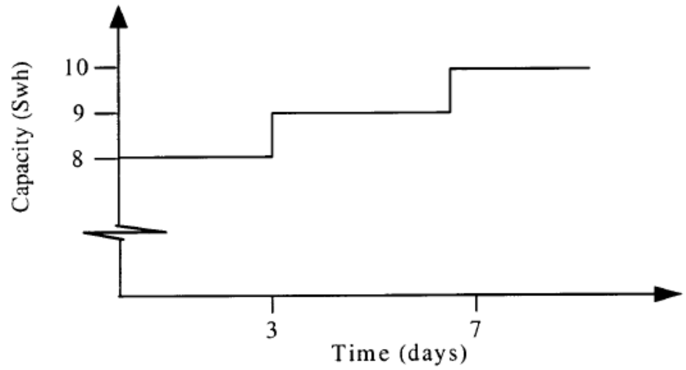
Hiring additional Worker: In some cases when the demand peaks, companies hire, additional worker. These workers are usually hired to perform low skilled jobs. In few of the cases, however temporary worker also perform high skilled works. Usually the worker are paid higher when they are hired temporarily.

Cross Training Worker: Cross training among the worker provides volume flexibility as well as mix flexibility to the company. The advantages of these could be realized to overcome the uncertainties related to worker absenteeism etc. This is one of the major source to overcome the uncertainties in the short run.

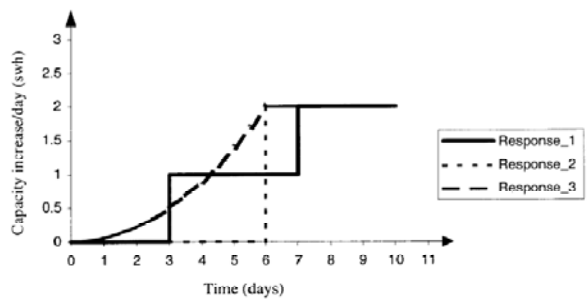
Overlapping Capability: At higher system levels, overlapping capability ranges among the machines provide volume flexibility. In case, these machines are dedicated to work on some specific range, then the system in consideration can not avail the flexibility offered by the overlapping range among the resources.

The notation and representation of this descriptor is different at different system levels. In general if 'Z' represents normal capacity/ unit time Z^u & Z^l represents the upper and lower bounds respectively on the capacity that can be reached in a considered time interval then the capacity range (CPR) of a machine can be represented by $CARA_{machine} = [Z^l, Z^u]$. At the work system level the representation of capacity range is quite complex. Since capacity & capability are interlinking & the available capacity of work system is distributed over the capability. Let NR^n represent normal capacity region in n- dimensional space. Where n represents the number of regions derived on the basis of critical driver of capability range. This region is a polyhydron rather than a polygon for $n \geq 2$ because the constraints boundries are hyper plane rather than a line. If NR^{nl} & NR^{nu} represents the lower & upper bound on the capacity region than the available capacity range of work system is given by

$CARA_{ns} = [NR^{nl}, NR^{ul}]$



CAPACITY RESPONSE: This descriptor indicates the effort required in varying the capacity along the time with in given capacity range. The efforts can be measured in terms of time or in terms of cost. In this paper we will consider this measure capacity response in terms of time. The capacity response is influenced by the policies adopted by manufacturing firm. If a company follows a policy to inform a worker three and seven days in advance to introduce 1 & 2 hours of overtime respectively and in normal case worker has to work standard eight hours per day then the capacity variation based on this policy, along the time will look like the curve shown in figure alongside. Usually, every company follows a unique policy of introducing overtime constrained by the government regulations. The capacity response curves can be derived from above curve by normalization as shown in figure 4. From time 0 to three days there is no capacity increase, and at day 3 and 7 there is an increase in the capacity for one and two hours respectively.



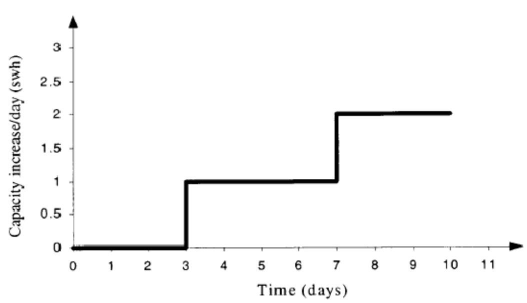


Figure 4: **CAPACITY RESPONSE**

Figure 5: **VARIOUS CAPACITY RESPONSE**

Although, the capacity increase curve provides a lot of insight when comparing the capacity response flexibility of two system, it is sometimes difficult to determine which system is more flexible in terms of capacity response. For an example in figure 5,which depicts the capacity responsive curve of three systems 1,2 and 3, it is difficult to answer straight forward, just by looking at the curve, which one is more capacity responsive. To facilitate comparison we propose the cumulative capacity increase over time, which is simply derived by the integration of the capacity response curve. In general, if the capacity response overtime is represented by function c (t) then the cumulative capacity response C (T) can be is given by expression

$C(T) = \int_0^T C(t)dt$

In case c (t) is a discontinuous function along the time as shown below

$$c(t) = \begin{cases} C1(t) & 0 \leq t \leq t1 \\ C2(t) & t1 \leq t \leq t2 \\ C3(t) & t2 \leq x \leq T \end{cases}$$

Then the expression of cumulative capacity response C (T) can be given by the following expression

$$C(T) = \int_0^{t1} c1(t)dt + \int_{t1}^{t2} c2(t)dt + \int_{t2}^{T} c3(t)dt$$

The cumulative response curve for a given capacity is as shown in figure 6. As can be seen from the figure system 3 is the best in terms of capacity response over the time which system 2 is the worst.

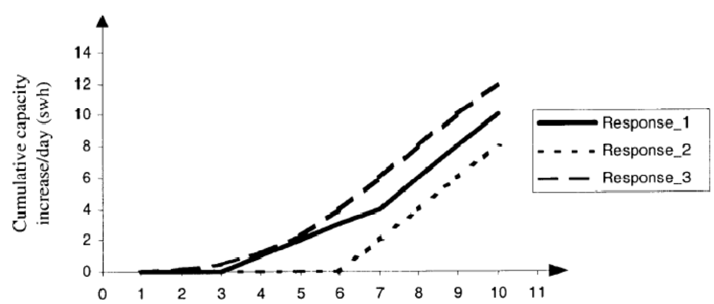


Figure 6: Cumulative Capacity Response Along The Time

From the figure 5, one might misjudge that system – I is more capacity responsive than system – 3 at least in some time intervals, as it provides a higher capacity between 3 days to 4 days. Similarly, system 2 is more capacity responsive from days 6 to day 7. However, from figure 6 it is evident that is not the case. At higher system levels, the capacity response can be derived in a similar way with some modifications. Specially, at the work system level, machine may possess overlapping capability range. Hence, the capacity increment over the complete range may not be uniform. Moreover another complexity comes in because of multiple drivers. To overcome this problem, we need to evaluate the following ratio:

$Cap_{rel.} = Cap / Cap_{normal}$

Where Cap_{rel} = Relative capacity (%)

Cap = Available capacity (Inclusive of option to increase capacity) of a work system [Std hours/ Periods]

Cap_{normal} = Normal available capacity of work system.

The plot between Cap_{rel} versus time has the same form as shown in figure 4 From that cumulative capacity response can be derived and also the overall system capacity response at higher system levels can be evaluated on the basis of following equation:

$$Cap_{rel, sys}(t) = Min\ [Cap_{rel,1}(t), Cap_{rel,2}(t)\text{--------}Cap_{rel,g}(t)]$$

Where

$Cap_{rel, sys}(t)$ = Relative capacity of cell (%)

$Cap_{rel, i}(t)$ = Relative capacity of a work system I (%)

MEASUREMENT OF THE INHARENT & REQUIRES FLEXIBILITY AT VARIOUS LEVELS: There are various levels of characterization . Figure 7 shows the vertical classification.

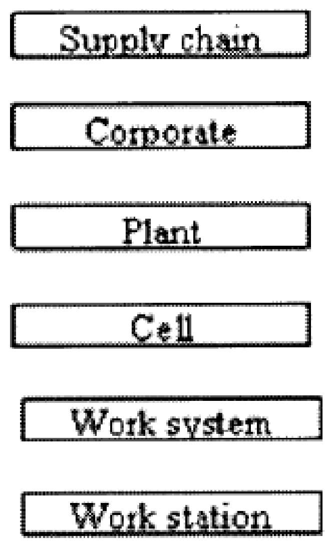


Figure 7 Hierarchical levels

Most of the vertical classification starts from basic resource level consisting of machine or a worker or a material handling equipment. However in this paper we consider workstation as the basic level. Workstation consists of a machine & a worker to perform the operation. Usually the capabilities of a workstation are the intersection of the capabilities possessed by the machine and the worker respectively. Characterizing machine flexibility without taking into consideration worker flexibility in some situation may lead to incorrect estimation. A work system consists of a machine or a group of machine with identical or different processing capabilities & efficiencies along with the workers. A cell consists of a several work system with different capabilities. A plant level usually consists of several cells, whereas at the corporate level there may be several plants. The supply chain usually includes several companies with supplier relationship serving the end customers.

Relationship between different levels needs to be established in order to develop an integrated view on manufacturing flexibility. The inherent & required flexibility at various system levels share a hierarchical relationship a shown in figure 8

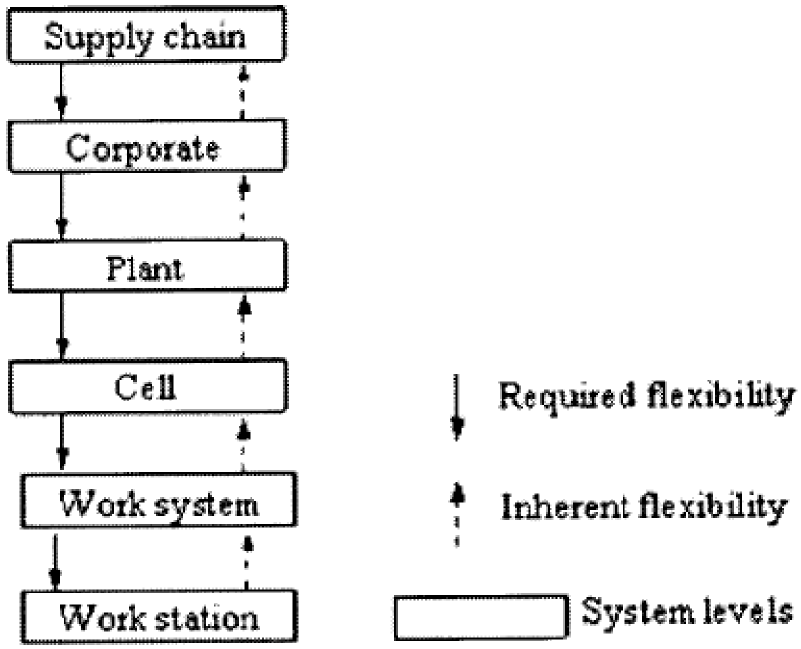


Figure 8: Hierarchical relationship between inherent & required flexibility

The proposed classification facilitates analyzing the impact of resource changes made at one level. In other words, an integrated view on manufacturing flexibility throughout the system could be established. Here we confined our discussion to develop flexibility measurement at the work station and at work system level only.

Measurement of flexibility can further be divided into following aspects like workstation levels, workstation with unique capabilities, similar efficiency across the capability range, machine with varying efficiency across the capability range, machine with multi-capabilities. Measurement of the inherent flexibility of the work system is done taking into consideration various aspects like identifying capability region and establishing relationship between regions with similar and different efficiencies.

CONCLUSIONS

Recognizing the importance of flexibility in dealing with the uncertain environment we have to conceptualize, characterize and measure flexibility. A different perspective about the flexibility concept is provided which enables treating flexibility as an inherent property of the system. The characterization of flexibility in the form of capacity and capability facilitates developing an integral treatment of flexibility throughout the manufacturing system. The impact of making change at one level on different system levels is established based on hierarchical framework. The measurement of flexibility in the form of equations provides a base for various applications. Moreover the comprehension of flexibility in the form of feasible space bounded by the systems of equations provides more comprehensive picture about the flexibility in the system. In real industry the concept of flexibility remains in the manager's mind and it is difficult for them to put it in real practice. The proposed way facilitates them planning, monitoring and managing the flexibility of their manufacturing resources in a system. This is specifically important in situation when response is critical, the future demands are difficult to forecast and error tolerance is relatively small.

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