Approach to Characterize Manufacturing Flexibility

Abstract

Flexibility is a key requirement for manufacturing companies to cope with the ever increasing turbulent environment. Though the ongoing discussion on flexibility has contributed much to the conceptual understanding of the nature of flexibility, it is still far from being characterized. We propose a systematic two-step approach to characterize flexibility. In the first step, conceptual frameworks are proposed to decouple flexibility from changes in the operating environment and from the performance criteria. This facilitates treating flexibility as an absolute concept. In the second step, the intrinsic properties of production system are extracted in the form of four flexibility descriptors namely: capacity range, capacity response, capability range, and capability response, to enable flexibility characterization. The focus is on volume and mix flexibility, as we believe these flexibility types are the most important ones from the operational perspective. The usage of the proposed descriptors is elaborated for the workstation level.

Keywords: Flexibility, Capacity, Capability, Manufacturing
1. Introduction

Flexibility has been well recognized as one of the key competitive advantages for any manufacturing firm. It is particularly important in dealing with the current manufacturing environment with a growing dominance of high mix and low volume production, increased customer expectations, along with the prevailing uncertainties (Swamidass, 1985, Gerwin, 1987, Barad and Sipper, 1988, Mandelbaum and Buzacott, 1990, Slack and Correa, 1992, Toni and Tonchia, 1999, Chang et.al., 2002). Though the ongoing discussion on flexibility has contributed much to the conceptual understanding of the nature of flexibility, a defined approach to characterize and measure flexibility remains a research issue. Sethi and Sethi (1990) argue that flexibility is a complex, multidimensional, and hard to capture concept. Similarly, Upton resumes in 1995, “ten or 15 years ago, quality was much like what flexibility is today: vague and difficult to improve yet critical to competitiveness”. One of the main difficulties in the development of objective measures of flexibility is its characteristics of being a potential (Tidd, 1991) and its inherent multi-dimensionality (Sethi and Sethi, 1990). Plethora of measures developed in past decades attests this claim. We believe the major obstacle in developing measures of flexibility is the absence of a well-defined approach to characterize flexibility. This is one of the main reasons why manufacturing industries find it extremely difficult to incorporate flexibility as a tool in dealing with the high variety low volume production environment. The fact is that, in industries, even though millions of dollars have been invested in flexibility (such as FMS equipment, training or advanced information technology systems) it is often difficult to demonstrate improvement in these areas as a result of these investments; consequently, flexibility characterization, meaningful measurement, comparison and analysis are still a topic of research.
In this paper we propose a two-step approach to characterize flexibility. Based on the characterization, the measurement of flexibility at workstation level is discussed. The ultimate goal is to enable manufacturing professionals to plan, monitor and manage the flexibility of their manufacturing resources, particularly in situations when response is critical, future demands are difficulty to forecast and error tolerance is relatively small. The discussion, in this paper, will be confined to operational flexibility, namely, volume and mix flexibility. Volume and mix are the most important flexibility types from the operational perspective. New product flexibility, expansion flexibility etc. are the flexibility types that are more relevant from strategic perspective and are important for the decisions related to manufacturing system design. They are beyond the main theme of discussion of this paper. The organization of the paper is as follows: In section 2, proposed approach, of flexibility characterization, is described in detail. Section-3 presents four flexibility descriptors. In section-4 use of these descriptors at the workstation level is discussed. Finally, conclusions are presented in section-5.

2. Flexibility Characterization

The first step of the proposed approach, to characterize flexibility, focuses on examining the relationship between flexibility, environment and performance issues. The definitions proposed by most researchers directly or indirectly link flexibility with changes in the operating environment, with performance criteria, or with both (Nof et.al. 1989; Buzzacott, 1982; Radcliffe, 1996; Chryssouris, 1992). While we certainly agree with these definitions in principle, the mutual entanglement of flexibility measures with changes in the operating environment and performance criteria such as makespan or on time delivery hinders the development of an independent measure and makes flexibility benchmarking very difficult, if not impossible. Hence, we propose to decouple flexibility measures from the changes in the operating
environment and from performance measures. This is similar to the idea of decoupling the conceptual understanding of quality from the “economics” of quality or from “luxury”. We propose to distinguish between the inherent flexibility and the required flexibility. The inherent flexibility is determined by the potential of the technological resources and workers and by organizational decisions (layout design, number of hours in a work shift etc.). The required flexibility is determined by the changes in the operating environment, the manufacturing strategy and the performance criteria. Henceforth, the flexibility of the system refers to the inherent flexibility. The implications of the proposed decoupling are that (inherent) flexibility can be described irrespective of the changes in operating environment. The comparison of the required and the inherent flexibility helps to determine whether or not 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. Then, the system does not have the right kind of (inherent) flexibility.

Similarly, the purpose of flexibility is to contribute towards the performance as emphasized in the definitions, flexibility is not the only factor contributing to a system performance. 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. Thus, poor performance not always is a reflection or indicator 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 flexibility (inherent). While this assumption may be true for few of the cases, it certainly does not remain valid in a general case.
Most of the systems we intend to compare may follow different manufacturing strategies and control procedures and may be subject to different environmental uncertainties.

The second step is to perform the system analysis, where the intrinsic properties of the production systems are extracted in order to characterize flexibility. To accomplish this we modified and extended the three aspects of flexibility characterization proposed by Upton (1994) as follows:

**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 quantity. For example: the number of products currently produced by the company is a “demonstrated” quantity, however, the number of products this company is capable to produce depicts a “potential”. To link this characteristic of flexibility with the intrinsic property of the production system, one should ask what are the elements that provide the ability to change. The volume flexibility is mainly concerned with the magnitude of change while mix flexibility is concerned with the changes in the type of mix. Capability and Capacity are the elements responsible for systems ability to change. This is because; volume flexibility requires capacity and mix flexibility requires various capabilities of the resources. Hence, capacity and capability are identified as the elements providing the ability to change.

**Dimensions**: Flexibility is a multi dimensional concept and this view has been agreed upon by all the authors. Range and Response are the two commonly agreed dimension reported in the literature (Slack, 1987; Gerwin, 1993; Koste and Malhotra, 1990; Beach, 2000). Range commonly refers to the number of different positions, or flexible options that the system in consideration can attain. Response corresponds to the “ease of movement” within the given range and can be measured in terms of cost or time. Since, capacity and capability provide an
ability to change; this change can be in two dimensions, “range” and “response”. In other words capacity and capability, both, can change in terms of range and response. Based on this understanding we propose following four descriptors to characterize mix and volume flexibility.

1. Capability range;
2. Capability response
3. Capacity range
4. Capacity response

**Time Horizon**: Capacity and Capability are the enablers for the potential of system in consideration. Capacity and Capability of the system are subject to change. However, the changes that may occur are constrained by the considered time horizon. If the duration is longer, the possible means to enhance the capacity and capability are different in comparison to the case where the duration is short.

**Inter and intra level relationship**: There exist interdependencies among the different flexibility types with in and between various system levels. A good characterization should be able to capture these relationships and should facilitate developing integral flexibility measures at various system levels. We believe hierarchical classifications proliferates number of flexibility types. The classification scheme proposed by Gerwin (1993) is one such attempt, which tries to address this issue. The proposed seven flexibility types (please refer to the literature review), according to Gerwin, are applicable at various system levels with some modifications. However the flexibility types proposed by him are not conceptually distinct. For example, mix and volume flexibility have inter dependencies. The flexibility characterization should be capable of addressing these inter dependencies. Hence, there is a need to establish the relationship between the four descriptors described above.

Further, to facilitate the integral treatment of flexibility in a manufacturing system, a hierarchical relationship between the flexibility types at various system levels needs to be established. Many researchers (Koste and Malhotra (1999), Beach et al. (2000)) have outlined the importance of
establishing the hierarchical relationship. However, no systematic and quantitative approach has been reported so far. The main reason behind this is the focus of measuring flexibility types independent of each other. This hinders the efforts put in developing integral flexibility with in a manufacturing system. The proposed descriptors facilitate establishing this relationship. Moreover, in future, the remaining flexibility types, other then the mix and the volume flexibility, proposed in Gerwin´s classification (1993) may be subsumed with in the proposed descriptor.

3. Flexibility descriptors

The four flexibility descriptors are capable of capturing and representing the nature of flexibility in a simple yet effective way. The details of these descriptors are outlined below. The application of these descriptors, at workstation level is described in the following section.

3.1 Capacity range:

This descriptor indicates the range in which the capacity of a system can vary. It is linked with the magnitude and can be measured in any convenient unit i.e. standard working hours (SWH) or parts per unit time. In this work, the capacity of all resources, including resources with different capabilities and efficiencies is measured in standard working hours (swh) as a common unit. This avoids a plethora of resource specific measures. The capacity of the system can vary due to many factors. These factors can be divided on the basis of time duration namely: short term sources and long term sources. Since the focus of this research is on operational perspective, we will focus more on short term sources. The major short term sources that facilitate varying the capacity of a system are:

A) 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 variations in demand are quite high. In addition to the variation in demand, in few of
the companies, rework is also an issue. To meet the deadline promised to customers, companies usually introduce overtime to compensate the rework or increase in aggregate demand. The amount of overtime is dependent on the company policies and also its constrained by the rules on overtime imposed by the central/state government.

B) 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 equipments. The second shift could be full staffed to increase the capacity of the plant. In some other case companies introduce additional shift on weekends to overcome the surge in demand.

C) Hiring additional workers: In some of the cases, when the demand peaks, companies hire additional workers. These workers are usually hired to perform low skilled jobs. In few of the cases, however, temporary workers also perform the high skilled tasks. For example: In garment industries, especially in China, in few of the regions e.g. Dunguan (Guandong province) it is easy to find skilled temporary workers capable of performing the sewing job which is supposed to be highly skilled task. Few of the Garment manufacturers even claim that these workers have better skills in comparison to the permanent worker they have in their organization and they usually have to pay higher salary to these temporary workers.

D) Cross trained workers: Cross training among the workers provides volume flexibility as well as mix flexibility to the company. The advantaged of this could be realised to overcome the uncertainties related to worker absenteeism etc. This is one of the major sources to overcome the uncertainties in the short run.
Consider the case of overtime to demonstrate the concept of capacity range. For example under a one-shift-policy the normal capacity of a work system may be 8 SWH. However, by overtime it can be increase up to 10 SWH. In general, if “N” represents normal capacity/unit time, N\text{u} and N\text{l} represent the upper and lower bound respectively on the capacity that can be reached in a considered time interval, then the capacity range can be represented by the set “S” as stated below.

Capacity Range: \( S = [N\text{l}, N\text{u}] \)

The capacity range is usually constrained by working time pattern of the employees, and by number of machines in a group. Usually, an agreement on working times specifies the number of hours an employee works under normal conditions and how much it can be increased by overtime or by working on weekends.

**3.2 Capacity Response:**

This descriptor indicates the efforts required in varying the capacity along the time with in a given capacity range. The efforts can be measured in terms of time or in terms of cost. In our work, we will measure capacity response in terms of time. The capacity response is influenced by the policies adopted by manufacturing firms to introduce overtime. For example: if a company follows a policy to inform a worker three and seven days in advance to introduce 1 and 2 hours of overtime respectively and in normal case worker has to work for 8 standard hours per day then the capacity variation, based on this policy, along the time will look like the curve shown in figure-1. Usually, every company follows a unique policy of introducing overtime constrained by the government regulations. The concept of capacity curves is introduced by Breithaupt and Wiendahl (2001).
The capacity response curve can be derived from the above curve by normalization as shown in Figure 2. From time 0 to 3 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.

Although the capacity response curves provide a lot of insights when comparing the capacity response flexibility of two systems, it is sometimes difficult to determine which system is more flexible in terms of capacity response. For an example, in figure 3, which depict the capacity response curve of three systems 1, 2, and 3, it is difficult to answer straightforward, just by looking at the curve, which one is more capacity responsive. If “x” represents the time and c(x) represents the capacity increase per day, then the mathematical representation of the three curves is as follows:
To facilitate comparison, we propose the cumulative capacity increase over time, which can be simply derived by the integration of the capacity response curve. In general, if the capacity response over the time is represented by function $c(t)$, then, the cumulative capacity response, $C(T)$, can be given by the following expression:

$$C(T) = \int_{0}^{T} c(t)dt$$

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

$$c_1(t), \quad 0 \leq t < t_1$$
$$c(t) = \begin{cases} c_2(t), & t_1 \leq t < t_2 \\ c_3(t), & t_2 \leq x < T \end{cases}$$

where $c_1$, $c_2$, and $c_3$ are different functions over different time intervals.
Then, the cumulative capacity response, \( C(T) \), can be given by the following expression:

\[
C(T) = \int_{0}^{t_1} c_1(t)dt + \int_{t_1}^{t_2} c_2(t)dt + \int_{t_2}^{T} c_3(t)dt
\]

The cumulative response curve, for a given capacity response (refer figure-3), is as shown in figure-4. As can be seen from the figure, system-3 is the best in term of capacity response over the time while system –2 is the worst. From figure-3, one might misjudge that system-1 is more capacity responsive than system-3 at least in some time intervals, as it provides a higher capacity between day 3 to day 4. Similarly, system-2 is more capacity responsive from day 6 to day 7. However, from figure-4 it is evident that is not the case.

![Cumulative capacity responses along the time](image)

**Fig 4: Cumulative capacity responses along the time**

### 3.3 Capability Range:

It depicts the application domain of the system under consideration. It is characterized by the combination of technical system constraints and some defining characteristic of an output. The capability of two machines is the same if they can produce the same set of existing or non-existing products (with the same quality). Thus, if the capabilities of two machines differ, there must be an existing or non-existing product that can be produced by one but not on the other machine. Usually it will be possible to identify technical system constraints responsible for this.
In some cases it might be the working space that determines the size of a product that can be processed by machine or in other cases it may refer to processing parameters such as drilling diameter. For example, in PCB industries, for drilling, typical technical system constraint is the drilling diameter. These technical system constraints are referred as capability drivers. The minimum number of capability drivers depends on the desired level of accuracy, varying efficiency and overlapping capabilities among the set of resources in the system under consideration. As the number of capability drivers increases the accuracy of identifying the inherent potential increases. Consequently, the greater the desired level of accuracy, the larger the number of drivers required to achieve that accuracy.

In general, if “X” represents the capability, in terms of technical system constraints/capability drivers of the system, \( X^u \) and \( X^l \) represents the upper and the lower bound respectively on the capability driver that can be achieved, then the capability range can be represented by set “CR” as follows:

\[
\text{Capability Range: } CR = [X^l, X^u]
\]

This range may be discrete as in the case of drilling machine or continuous as in the case of furnace where the temperature can vary in a continuous range. If in case discrete points are close enough in the set, they can be treated as a continuous range.

### 3.4 Capability response:

This descriptor indicates the efforts required to switch from one point in the set CR, representing the capability range, to another point in the set. The lower the capability response is, the easier it is to deal with a high product variety. The classic measure for capability response is set up 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 and for sake of simplicity it is
assumed to be machine dependent. For each capability attribute it is always possible to define both capability range and capability response. However there are cases, in which set up time is zero for critical attributes of capability range. In this case the attribute is only critical for capability range. And there are cases, in which set up time is non zero for non-critical attributes of capability range. In this case the attribute is only critical for capability response. In other words, the critical attributes of capability range and capability response may be different. We can easily think of a portfolio (critical / non critical for capability range vs. critical / non critical for capability response) and classify all the attributes in that.

4. Flexibility measurement at workstation level

The single machine workstation is the most basic case. The term workstation here refers to the combination of a machine and a worker. If this workstation performs the drilling operation, then the descriptors can be represented as shown in figure 5.

![Diagram](image)

**Fig 5: Descriptors for single machine workstation**
As shown in the capacity range, the capacity of the workstation can vary from eight to ten standard working hours per day. Workers are informed respectively three, seven days in advance for respectively one and two hours of overtime. Hence, increase in capacity from eight to ten standard working hours needs one working week of response time. Usually working time policies differ from company to company.

The capabilities of the workstation are the intersection of the capabilities of a machine and a worker. For example: if a worker is capable of performing three operations (O₁, O₂ and O₃) and a machine can only perform one operation (O₁), then the capability of the workstation is to perform only operation O₁. In the above figure, the capability range of the workstation is to perform drilling with diameters ranging from 2-8 mm. The capability response indicates the efforts required in changing the tool bit for a change in diameter in the given capability range. This is measured by the set up time, which is fairly small for this case. The capacity range, capacity response and capability range can be combined into one representation as shown in figure 6.

![Figure 6: Overall representation](image)

**5. Conclusions**

In this paper, we presented a two step approach for flexibility characterization and measurement. In the first step we argued decoupling from the influences of environment and performance
criteria. In other words, flexibility is being treated as an inherent property of the system and thereby absolute measured could be developed based on that understanding. In the second step, we performed system analysis, where intrinsic properties of the production system are mapped with the nature of flexibility. Based on the two steps, we identified four flexibility descriptors to characterize mix and volume flexibility and their interactions at various system levels. The identified descriptors are capacity range, capacity response, capability range, and capability response. The demonstration of the usage of these descriptors at workstation level is discussed. Similar discussion could be extended to work system level, consisting of parallel workstations, and to other higher system levels.

6. References


