The International Journal of Flexible Manufacturing Systems, 10 (1998): 325–349

Definition and Classification of Manufacturing Flexibility Types and Measures

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Abstract. Flexibility is one of the most sought-after properties in modern manufacturing systems. Despite this interest, flexibility remains poorly understood in theory and poorly utilized in practice. One reason for this is the lack of general agreement on how to define *flexibility*: over 70 terms (types and measures) can be found in the literature. This paper concerns developing a framework and classification scheme for use in defining and classifying the various terms regarding flexibility found in manufacturing. The framework consists of six attributes: level of manufacturing requirements specification, manufacturing system specification, manufacturing environment specification, flexibility dimension, flexibility measurement approach, and time frame. A six-field hybrid classification scheme is developed based on this framework. The framework serves as a guide for developing new flexibility terms, whereas the classification scheme provides a mechanism for summarizing the important aspects of and assumptions behind a given term. The approach is demonstrated by using the classification scheme to classify over 50 existing flexibility terms. The results indicate that the classification scheme is an effective tool to aid in understanding different flexibility terms and how they compare to one another. At the same time, the difficulty of the classification exercise indicates the need for a suitable framework when defining such terms.

Key Words: flexibility, flexibility types, flexibility measures, manufacturing systems

1. Introduction

A great deal of research in defining various types of flexibilities in manufacturing has occurred over the last two decades. Despite this, there is no general agreement on how to define *flexibility*. At the outset, this is due to the multidimensional nature of flexibility and the various views of flexibility that result: flexibility has been viewed and studied as a physical property, an attribute of decision making, an economic indicator, and a strategic tool. In a comprehensive survey of the literature, Sethi and Sethi (1990) reported that at least 50 terms exist for the various types of flexibilities studied. Furthermore, they found that several terms refer to the same flexibility type in many cases and that definitions for flexibility types often are imprecise and conflicting, even for identical terms.

Before continuing further, it is necessary to define some terminology, as terms such as *flexibility types* and *measures* often are used loosely and somewhat interchangeably. A flexibility *type* consists of a name and a verbal definition of that type; for example, *routing flexibility*, defined as the “ease with which products can be processed using alternate machines or equipment." Different flexibility types could have the same name but different definitions or different names and the same definition. A flexibility *measure* is a formula, algorithm, methodology, or the like, for generating a *value* for a given flexibility type under given conditions. For example, a measure of routing flexibility could be the average quantity of alternate machine routes possible for the set of products considered. Given a flexibility type, multiple measures may be possible. The literature indicates that flexibilities most often are defined in terms of a type only; types and corresponding measures are found much less frequently. Based on this observation, we refer to either a flexibility type or a flexibility type and measure as a flexibility *term*. In this way, we can refer collectively to any flexibility found in the literature in a common manner—as a flexibility term.

The aforementioned problems now can be discussed. They result from three basic shortcomings regarding attempts to develop flexibility terms for manufacturing. The first is that terms have been based on different perspectives of what constitutes a manufacturing system and its environment. The second is that, in defining flexibility types and measures, researchers have had different ideas as to what information is required and the corresponding level of detail necessary to specify such information. Finally, as no formal mechanism for articulating flexibility type definitions and measures exists, the terms often are incomplete, imprecise, and insufficient in their level of detail to be clearly understood. Correa (1994) notes that the lack of standardization in the terminology about flexibility matters in the literature makes it difficult to compare different authors' classifications.

To address these shortcomings, three items are required. The first is a well-defined framework for modeling the manufacturing system and its environment. This should be detailed enough to ensure that flexibility terms can be developed based on a single notion of what constitutes a manufacturing system and its environment, but generic enough in nature that it does not restrict the domain of manufacturing systems that can be investigated. The second item is a framework for defining flexibility types and measures. This should serve as a guide for developing new terms: it should indicate which attributes must be specified and in what way. Third, for articulating flexibility terms in a common, precise manner, two approaches are possible. The first is to develop a detailed methodology for specifying flexibility type definitions and measures, detailing what information is required, to what extent, presentation order, and so forth. This approach is deemed undesirable in that it likely would be impossible to develop a methodology rigid enough to force consistency yet loose enough to be usable for a wide variety of flexibility terms and manufacturing domains. A different approach, which is used here, is to develop a classification scheme for flexibility terms. The objective is to provide a scheme for summarizing the important aspects of and assumptions behind a given flexibility term, in an unambiguous, clear, and concise manner, such that the basic idea behind and intent of a given term may be understood quickly and with minimal effort. For detailed information, the user then would need to refer to the actual flexibility type definition and measure (if provided). The use of such a classification scheme ideally would result in a workable compromise between the aforementioned conflicting objectives.

Using these items, flexibility terms can be defined in a common manner, even if they have been derived based on different models and assumptions. Furthermore, the classification scheme should provide not only a mechanism for aiding in developing flexibility terms, but also an effective tool to aid in comparing and understanding the relationships between existing terms.

2. Background

Despite the extensive effort expended in defining flexibility types, little work has been done to develop modeling frameworks, frameworks for classifying flexibility terms, or classification schemes. The vast majority of research has concentrated simply on identifying and defining flexibility types, based on specified models and assumptions. The research performed on the aforementioned tasks is summarized next.

Several researchers have attempted to develop, to varying extents, some type of modeling framework on which to derive or classify flexibility terms. Zelenovic (1982) uses a cause-and-effect diagram to illustrate the interaction of the production system with its environment. He describes the basic elements of both a system-environment model (system objective function, parameters of production systems) and production systems (system structure). He then develops a rudimentary foundation for an architecture for specifying manufacturing systems, but does not directly link this to the specification of flexibility attributes. Kumar and Kumar (1987) describe a simple system-environment model consisting of four elements—inputs, outputs, manufacturing process, and environment—to classify the types of uncertainty manufacturing managers must face. Brill and Mandelbaum (1989) develop a "production framework" for use in deriving measures of flexibility and inherent flexibility for a machine or group of machines. The framework is generic in nature; however, its applicability is limited because it consists of only a static view of the system. Finally, Benjaafar (1992) develops a combined manufacturing system-product model for deriving the various types of flexibilities found in manufacturing using a "bottom-up" approach. This research perhaps goes the furthest in identifying and defining flexibility types based on a given model and using a logical, structured approach.

Although few attempts, if any, have been made to identify all the various attributes required to define manufacturing flexibility types, many researchers have noted one or more of these attributes in the course of their work. Basic categories of flexibility have been noted by Mandelbaum (1978) and Slack (1987). Relative vs. absolute views of flexibility have been noted and discussed by Goldhar and Jelinek (1983), Jaikumar (1984), Gerwin (1987), Brill and Mandelbaum (1989), Gupta and Buzacott (1989), and Chryssolouris and Lee (1992). A classification of flexibility types based on uncertainty has been performed by Gerwin (1987) and Kumar and Kumar (1987), whereas classification based on the level of decomposition has been proposed by Gerwin (1987) and Taymaz (1989). Finally, researchers noting the time-dependent nature of flexibility include Gustavsson (1984), Gerwin (1987), Slack (1987), Barad and Sipper (1988), and Gupta and Buzacott (1989). These works shall all be elaborated on in Section 4.

Finally, no attempt at developing a rigorous classification scheme for flexibility terms has been found in the literature. Classification schemes serving a similar purpose have been developed in other areas, however. Group technology classification and coding schemes (e.g., Burbidge, 1975) represent a well-established methodology for representing the most important attributes of part types in simple, concise, easy-to-understand formats. More closely aligned with the intent of this research, however, is the classification scheme used for scheduling problems (Lawler, Lenstra, Rinnooy Kan, and Shmoys, 1990): such classifications indicate the domain, underlying assumptions, and constraints of a given problem.

3. Modeling framework

Before the framework for defining and classifying flexibility types and measures can be developed, the manner in which manufacturing systems and their environments are modeled must be defined. This is done as follows.

3.1. Manufacturing system

In the most basic sense, manufacturing systems consist of various machines (processing or assembly equipment, material handling equipment, inspection stations, etc.) and the operating and control algorithms used to determine how the equipment is to be operated. Together, these items determine the *capability and capacity envelope* for the system. In many cases, it may be cost or time prohibitive, too complex, and so on to make the entire capability and capacity envelope available simultaneously. An example of this is an FMS: the capabilities and capacities at any time depend (at least partially) on how the various machines are "tooled up" (i.e., what tools are loaded in the tool magazines). Thus, at any time, a particular subset of the system's capability and capacity envelope is available: the manufacturing system can be said to be in a particular *configuration*. A manufacturing system may move from one configuration to another in two ways. First, the configuration may be changed intentionally, to adopt a more favorable match between what capability or capacity is required (desired) and what is available. A certain amount of effort (time, cost, etc.) will be required to effect such changes. The second is when the configuration changes on its own due to component wear (e.g., changes in process capabilities, processing rates, etc.) or unreliability (e.g., machine breakdowns).

To focus on a particular aspect of the manufacturing system, different modeling concepts are used. We use of two of the most common modeling concepts for defining flexibility types and measures: level of decomposition and scope of view. *Level of decomposition* refers to the subset of the manufacturing system under consideration when the system is considered to be hierarchically structured. At the top level of decomposition, the manufacturing system is considered in its entirety: lower levels may correspond to departments, cells, workstations, and finally individual machines (Jones and McLean, 1986). *Scope of view* refers to which elements of the manufacturing system, at a given level of decomposition, are under consideration. For example, at the department level, we may wish to consider all the machines, material handling devices, control algorithms, and the like, or some subset of these items.

3.2. Manufacturing environment

The manner in which the system interacts with the environment, or system-environment model, is illustrated in figure 1. The function of the system is to transform a given stream of

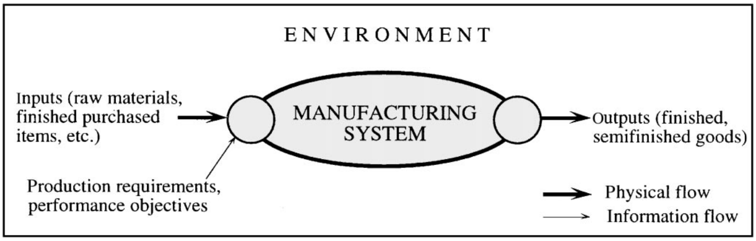

Figure 1. Manufacturing system in its environment.

inputs (raw materials, purchased finished items, etc.) into *outputs* (finished and semifinished goods), in accordance with the specified *production requirements*, while satisfying any specified *performance objectives* (maximize machine utilization, minimize WIP, etc.). Consider a manufacturing system operating over a given time interval of interest (in a single configuration or using multiple configurations). Production requirements can be specified in terms of two items:

1. *Product requirements*: what items are to be produced. We distinguish between different types of products to be produced sequentially and those to be produced simultaneously. The former will be called a *product set* (P) and the latter a *product mix* (PM).
2. *Production scenarios* (PS): when the products constituting a given set or mix are to be made (i.e., what rates to use, release schedules, etc.) during the time interval of interest.

Inputs also can be specified in terms of two variables:

1. *Input definitions* (I): what types of items enter the system, in terms of various attributes (material type, dimensions, geometry, physical or mechanical properties, quality, etc.).
2. *Input arrival patterns* (IA): when items are to arrive to the system and in what quantities.

3.3. Production states

A particular combination of the preceding items—system (single or multiple configurations), production requirements, performance objectives, and inputs—designates a *production state*. We can consider two types of production states, based on the production requirements and inputs considered.

First, consider that production requirements consist of a single product or product mix, and inputs are specified by input definitions only. In this case, the ability of the manufacturing system to perform the transformation can be evaluated based solely on the capabilities of the system with respect to the desired product(s) and available inputs. As this is all static data, we can refer to such production states as *static production states*. If the transformation associated with a static production state can be performed, we say the state is *capable*. This means that the manufacturing system is capable for the given product(s) and inputs.

Conversely, we can refer to the product(s) as being capable; that is, P_C (single product) or PM_C (product mix).

Next, consider that production requirements consist of a single product (or product mix) and single production scenario: inputs are specified by input definitions and arrival patterns. In other words, we have a static production state plus a production scenario and input arrival patterns. Furthermore, the system is capable of the transformation. In this case, we can now evaluate the ability of the manufacturing system to be capable over time; that is, to be *stable* for the production requirements and system inputs. The exact meaning of stability must be defined on a case-by-case basis: in some instances, it will refer to "steady-state" operation; in others, the ability to operate within specified limits for the specified time interval. In any case, this ability depends on the capacities of the manufacturing system with respect to the production scenario and input arrival pattern. As this can be evaluated only by considering the dynamic behavior of the system, we refer to such production states as *dynamic production states*. If the transformation associated with a dynamic production state can be performed, we say the state (manufacturing system) is *stable*. We also can refer to the production scenario as being stable, PS_S.

3.4. Changes in production state

Although we may start with an initial production state, there is no guarantee that the state will persist over time. A variety of factors may cause changes in production state to occur. How can such changes be defined? Correa (1994) describes five attributes required to define change: novelty (nature of the change), size (magnitude of change), frequency (of occurrence of a given type of change), certainty (that a given change will occur), and rate (how often changes occur in a given period of time). It is not possible to consider each of these aspects of change and still maintain a tractable modeling framework and classification scheme. Therefore, we concentrate on the nature of change, the certainty associated with a given type of change, and how often changes of a specified type occur. Based upon the system-environment model, the different types of changes which may occur fall into three categories:

- *Changes in production requirements*: changes in product definitions, product mixes, production scenarios, or various combinations of these.
- *Changes in system inputs*: changes in input definitions (e.g., material condition out-of-specification, incorrect dimensions, tolerances, geometry, etc.) and input arrival patterns (e.g., late delivery times).
- *Changes in the system itself*: changes in the capabilities or capacities available, or system configuration, due to component wear and unreliability.

Each of these types of change results in multiple production states. How often changes of a specified type occur can be determined by the quantity of changes occurring during the time frame of interest.

3.5. *Coping with changes in production state*

How can manufacturing systems cope with different types of changes that may occur? Based on the preceding framework, we can distinguish among three fundamentally different approaches. The first is to utilize the internal ability of any given system configuration for taking alternative, corrective actions in response to change. In this case, a single system configuration is employed. In the event that the types or levels of change are too severe for a single system configuration to handle, the system configuration must be changed; that is, multiple system configurations must be used. If the ability to handle the changes still is within the capability and capacity envelope, the change may be made internally, i.e., to another system configuration within the present capability and capacity envelope. On the other hand, if the ability to handle the change is beyond the capability and capacity envelope, the change must be made externally, i.e., the capability and capacity envelope itself must be changed and a suitable system configuration then selected from the new envelope.

4. Flexibility framework and classification scheme

Based on the modeling framework, we can develop a framework for defining flexibility terms and a corresponding classification scheme. The framework consists of six attributes: level of manufacturing requirements specification, manufacturing system specification, manufacturing environment specification, flexibility dimension, flexibility measurement approach, and time frame. A six-field, hybrid classification scheme—$\alpha/\beta/\gamma/\eta/\upsilon/\tau$ is developed. Each framework attribute, and the manner in which its corresponding field is specified, is described next.

4.1. *Level of manufacturing requirements specification, α*

The first question to be answered in establishing a flexibility term is, What is the flexibility pertaining to? The manufacturing system in isolation? Or, the system and some particular production requirements and inputs? If the latter, are we interested in the ability of the system to be capable or stable? Finally, by *ability*, do we refer to simply whether or not the system is capable (stable) or the *extent* to which the system is capable (stable)? These questions are answered by establishing which of the variables defining production states are fixed and which are free: we refer to this as the *level of manufacturing requirements specification*, α. Based on the modeling framework, five levels can be identified, as shown in Table 1. At the top level, only the manufacturing system is fixed: as we move down to lower levels, more variables become fixed. At the bottom level, all variables required for steady-state production to occur are fixed.

The terms for which $\alpha = \text{I}$ are absolute, whereas $\alpha = \text{II–V}$ indicates the term is relative. Absolute terms are those that view flexibility as an inherent property of the system; that is, flexibility can be determined with no reference to any particular production requirements. An example is flexibility terms indicating that FMSs are more flexible than transfer lines. Relative terms are those where flexibility has meaning only with respect to the production requirements or demands placed on the system. Terms for which $\alpha = \text{I, II, or III}$ are

Table 1. Production state variables fixed at each level of manufacturing requirements specification.

				Production requirements			
		Inputs		Product requirements		Production scenarios	
α	System configuration(s)	I	IA	P (or PM)	P_C (or PM_C)	PS	PS_S
I	x						
II	x	x		x			
III	x	x			x		
IV	x	x	x		x	x	
V	x	x	x		x		x

concerned with the ability of the system to be capable (static states), whereas terms for which α = IV or V are concerned with the ability of the system to be stable (dynamic states). Finally, terms for which α = II or IV are concerned with simply whether or not the system is capable (stable), whereas terms for which α = III or V are concerned with the extent to which the system is capable (stable).

The distinction between absolute and relative flexibility has been noted by several researchers. Jaikumar (1984), for example, states that flexibility in manufacturing systems always is constrained within a domain. Chryssolouris and Lee (1992) report two views of flexibility, the first is where flexibility is an "intrinsic attribute" of a manufacturing system and the second is where flexibility is a "relative attribute," depending on the external demands placed on the system. Brill and Mandelbaum (1989), in developing various measures of flexibility for machines, conclude that their measures "must be related to a reference task set for the measure to have any meaning." Other researchers to note this characterization include Goldhar and Jelinek (1983) and Gerwin (1987).

4.2. *Manufacturing system specification, β*

Given the level of manufacturing requirements specification, α, the next question to be answered is, what aspect(s) of the manufacturing system are we interested in? The entire manufacturing system or a particular subset of components? A single manufacturing system configuration over the time frame of interest or multiple configurations? The former question is answered by establishing the level of decomposition and scope of view. For simplicity, we consider only three levels of decomposition: facility, group, and machine. Similarly, we consider only two scopes of view: maximum scope (e.g., all machines, material handling devices, control algorithms, etc., at the group level) and restricted scope (e.g., machines only). The latter question is answered directly. This information can be specified as follows:

$$\begin{aligned}\beta &= \text{manufacturing system specification}\\ &= \{\beta_1, \beta_2\}\end{aligned}$$

where

$$\begin{aligned}
\beta_1 &= \text{level of decomposition and scope of view of manufacturing system}\\
&= F,\ \text{facility level, maximum scope}\\
&= f,\ \text{facility level, restricted scope}\\
&= G\ (g),\ \text{group level, maximum (restricted) scope}\\
&= M\ (m),\ \text{machine level, maximum (restricted) scope}\\
\beta_2 &= \text{quantity of manufacturing system configurations over time frame of interest}\\
&= 1,\ \text{single configuration}\\
&= n,\ \text{multiple configurations}
\end{aligned}$$

The level of decomposition has been used as a classification mechanism for flexibility terms by several researchers. Jaikumar (1984) states that flexibility is obtained at two levels, the machine level and the system level. Gerwin (1987) states, "A basic issue that must be resolved in defining manufacturing flexibility is the level at which it is to be considered," and suggests various alternatives, including manufacturing functions (processes), individual machines, manufacturing processes for single products or groups of products, factories, and the entire factory system. Taymaz (1989) develops three levels of analysis for defining flexibility terms: component, operations, and system.

Although the scope of view has not been explicitly suggested as an attribute for defining flexibility terms, examples can be found where this variable clearly plays an important role. For example, routing flexibility as defined by Gerwin (1982) and Browne, Dubois, Rathmill, Sethi, and Stecke (1984) is dependent on the ability of the system as a whole, that is, the machines, control mechanisms, and the like (maximum scope), whereas routing flexibility as defined by Chung and Chen (1989) and Chandra and Tombak (1992) is dependent on only the machines (restricted scope). Another example is provided by Gupta and Buzacott (1989), who note that "increasing the number of possible routes that material handling systems (for example, the automated guided vehicles) might take does not necessarily increase flexibility unless the control mechanism takes advantage of the multiplicity of routes."

4.3. *Manufacturing environment specification, γ*

Once the level of manufacturing requirements specification, α, and manufacturing system specification, β, are established, the nature of the manufacturing environment can be specified. Based on the modeling framework, the first item that can be specified is whether we are dealing with a single or multiple production states. If a single state, we should specify whether the production requirements consist of a single product, a single product mix, or a single combination of product (product mix) and production scenario (and associated inputs in each case). If multiple states, we are concerned with the various change attributes described in Section 3.4. First of all, what type of change is occurring? As stated, the type of change can be specified in terms of the category of change (production requirements, inputs, or system), and what variable(s) are changing. Second, what level of uncertainty is associated with such changes? For the purpose of classification, this can be answered simply by stating whether or not the changes are considered to be deterministic (no uncertainty) or probabilistic. Finally, how many changes are we dealing with? Again for the purpose of classification, this can be answered simply by specifying whether we are interested in what would be considered a restricted set of changes, or the "universe" of all possible changes. This information is specified as follows:

$$\begin{aligned}\gamma &= \text{manufacturing environment specification}\\ &= \{\gamma_1\ (\gamma_2) : \gamma_3, \gamma_4, \gamma_5\}\end{aligned}$$

where

$$\begin{aligned}\gamma_1 &= \text{nature of environment}\\ &= P,\ \text{single production state}\\ &= \Delta P,\ \text{multiple production states via changes in production requirements}\\ &= \Delta I,\ \text{multiple production states via changes in system inputs}\\ &= \Delta S,\ \text{multiple production states via changes in the system itself}\\ \gamma_2 &= \text{level of uncertainty associated with changes}\\ &= \text{(not used)},\ \gamma_1 = P\\ &= d\ \text{(deterministic changes)},\ \gamma_1 = \Delta P, \Delta I, \Delta S\\ &= p\ \text{(probabilistic changes)},\ \gamma_1 = \Delta P, \Delta I, \Delta S\end{aligned}$$

and γ_3, γ_4, and γ_5 take on different meanings, depending on γ_1, as follows:

$$\begin{aligned}\{\gamma_3, \gamma_4, \gamma_5\} &= \{\text{quantity of product definitions, quantity of product mixes,}\\ &\qquad \text{quantity of production scenarios}\},\ \gamma_1 = P \text{ or } \Delta P\\ &= \{\text{quantity of input definition sets, quantity of input arrival patterns,}\\ &\qquad \text{(not used)}\},\ \gamma_1 = \Delta I\\ &= \{\text{quantity of system configurations, (not used), (not used)}\}, \gamma_1 = \Delta S\end{aligned}$$

In all cases, each of γ_3, γ_4, and γ_5 can take on values as follows:

$$\begin{aligned}\gamma_i &= 1,\ \text{single item}\ (i = 3,\ 4,\ 5)\\ &= m,\ \text{restricted set of changes being considered}\ (i = 3,\ 4,\ 5)\\ &= M,\ \text{universe of all possible changes being considered}\ (i = 3,\ 4,\ 5)\\ &= \text{—},\ \text{variable not active.}\end{aligned}$$

Various combinations of values for γ_1 through γ_5 are possible, giving different manufacturing environments. These are summarized in Table 2.

Various researchers have noted the need to classify the different types of change that can result in the need for flexibility. Buzacott (1982), for example, considers two types of change: external (changes in type and mix of jobs, processing requirements, etc.) and

Table 2. Specification of different manufacturing environments.

	Manufacturing environment					
α	γ_1	γ_2	γ_3	γ_4	γ_5	Description of manufacturing environment
II, III	P	(n/a)[1]	1	—	—	Single product
	”	”	—	1	—	Single product mix
	ΔP	d, p	m, M	—	—	Changes in products
	”	”	—	m, M	—	Changes in product mix
	ΔI	d, p	m, M	—	(n/a)	Changes in input definitions
	ΔS	d, p	m, M	(n/a)	(n/a)	Changes in system configuration
IV, V	P	(n/a)	1	—	1	Single product and production scenario
	”	”	—	1	1	Single product mix and production scenario
	ΔP	d, p	1	—	m, M	Changes in production scenario, constant product definition
	”	”	m, M	—	1	Changes in product definition, constant production scenario
	”	”	m, M	—	m, M	Simultaneous change in both product definition and production scenario, $m(M)$ combinations
	”	”	—	1	m, M	Changes in production scenario, constant product mix
	”	”	—	m, M	1	Changes in product mix, constant production scenario
	”	”	—	m, M	m, M	Simultaneous change in both product mix and production scenario, $m(M)$ combinations
	ΔI	d, p	m, M	—	(n/a)	Changes in input definitions
	”	”	—	m, M	(n/a)	Changes in input arrival patterns
	”	”	m, M	m, M	(n/a)	Simultaneous changes in both input definitions and arrival patterns, $m(M)$ combinations
	ΔS	d, p	m, M	(n/a)	(n/a)	Changes in system configuration

[1](n/a) = field not applicable (not used).

internal (machine and material handling problems, variability in processing times, etc.). Many researchers discuss and categorize change in the context of uncertainty. Kumar and Kumar (1987) categorize uncertainty in terms of the “four elements of the manufacturing system”: inputs, outputs (end-product specifications and delivery times), manufacturing process, and environment (product demand and life cycles). Gerwin (1987) describes seven different sets of uncertainties: that with respect to (1) which products will be accepted by customers, (2) length of product life cycles, (3) which product attributes customers want (i.e., product variants), (4) machine downtime, (5) level of customer demand, (6) extent to which input materials meet standards, and (7) delivery lead times. Each of these different types of uncertainty results in changes which can be represented via the above modeling framework.

The need to consider the certainty with which given changes will occur in determining flexibility has been noted by several researchers. Buzacott (1982) notes that, in determining the flexibility of a system to process different types of jobs (*job flexibility*), the probability that each job will occur should be incorporated into the measure. Other works utilizing this concept include Brill and Mandelbaum (1989) and Chryssolouris and Lee (1992). Finally, various researchers have noted the importance of specifying the quantity of changes. Jaikumar (1984) states that any FMS is designed for a restricted domain of a particular family of parts, and only that family need be considered in defining flexibility for that FMS. Brill and Mandelbaum (1989) use task sets to specify the scope of production requirements.

4.4. Flexibility dimension, η

Given the level of manufacturing requirements specification, α, manufacturing system specification, β, and manufacturing environment specification, γ, we now turn our attention to the manner in which flexibility is specified. The most basic question regarding any flexibility term is, what do we mean by flexibility—the ability of a system to cope with change, the ease with which the system can adopt different configurations, or some other kind of flexibility? The basic interpretation of what is meant by flexibility, independent of a particular context, often is referred to as a *flexibility dimension*. Various flexibility types can exist for a given dimension. Therefore, flexibility dimension is of interest, as it can be used to classify different flexibility terms and answer the preceding question.

Gerwin (1993) states that, "most treatments of flexibility assume it is a multidimensional concept but provide no theoretical basis for finding its relevant dimensions." The objective here is to derive flexibility dimensions based on the modeling framework, using existing definitions of flexibility dimensions wherever possible. Correa (1994) reports 12 flexibility dimensions as proposed by seven different research efforts. These are *action* and *state* (Mandelbaum, 1978); *range* and *response* (Slack, 1987); *sensitivity*, *stability*, and *effort* (Gupta and Buzacott, 1989); *time* (Carter, 1986; Stecke and Raman, 1986); *organization* (Gerwin, 1987); and *range*, *switchability*, and *modifiability* (Dooner and De Silva, 1990). Correa notes that these dimensions are not unique: many similarities exist. Therefore, the goal is to try to utilize a subset of these terms that do not overlap yet cover the different interpretations of flexibility.

Consider first the manufacturing system in isolation. The greater is the ability to utilize the elements of the manufacturing system in alternative ways, the greater the flexibility of the system. We refer to this dimension as *operational flexibility*, as it relates to the ways in which a given system configuration can be operated. Operational flexibility can be obtained via either a single system configuration or multiple configurations. Concerning the use of multiple configurations, the larger is the set of different configurations possible (i.e., size of the capability and capacity envelope), the more flexible the system will be. This dimension is best described by *range flexibility*, after Slack (1987), who defines this as the "total envelope of capability or range of states which the production system or resource is capable of attaining." As noted by Slack, the range of states alone does not describe a system's flexibility: the ease with which the system moves from one state to another also is important. This dimension is *response flexibility*, defined by Slack as the "ease (in terms of cost, time, or both) with which changes can be made within the capability envelope." Finally, the set of different configurations possible (and hence flexibility) can be increased by changing the capability and capacity envelope itself. Therefore, the greater is the ability to change the capability and capacity envelope, the greater the flexibility. This dimension is called *action flexibility*, after Mandelbaum (1978), who defines this as the "capacity to take new action to meet new circumstances." Buzacott (1982) notes that a system has action flexibility if the intervention required to respond to change must come from outside the system.

Consider next a manufacturing system (single or multiple configurations) faced with a single transformation, in other words, a single production state. The greater is the ability to utilize the system elements to perform the transformation in alternative ways, the greater the flexibility of the system. This again is operational flexibility, the only difference being that the ability to use the system elements is with respect to some particular requirements. Note also that the range, response, and action flexibility dimensions also apply when multiple configurations are employed.

Finally, consider a manufacturing system (single or multiple configurations) faced with changes to production requirements, inputs, or the system itself. These changes result in multiple production states. The larger the quantity of states for which the system is capable (static states) or stable (dynamic states), the more flexible it is considered to be. The term *range flexibility* again applies: Slack notes that, "one production system is more flexible than another if it can exhibit a wider range of states or behaviors; for example, make a greater variety of products, manufacture at different output levels or delivery lead times, and so on." On the other hand, if it is known a priori that the system is capable (stable) for the given set of states, flexibility is best described in terms of how capable it is over the set of static states or how performance varies over the set of dynamic states. We refer to this as *state flexibility*, after Mandelbaum (1978), who defines *state flexibility* as the "capacity to continue functioning effectively despite change." However, we choose not to employ the qualifier *effective* in our definition: we will incorporate this aspect of flexibility via the flexibility measurement approach (described in the following section). Again, the range, response, and action flexibility dimensions also apply when multiple system configurations are employed.

One last point needs to be made. We can refer to any flexibility dimension (or term) having to do with a single configuration as flexibility at a time (as any of the means by which the flexibility is obtained are all available at a given time) and with multiple configurations as flexibility over time (as the opposite is true).[1] Summarizing,

$$
\begin{aligned}
\eta &= \text{flexibility dimension}\\
&= O,\ \text{operational flexibility}\\
&= R,\ \text{range flexibility}\\
&= Re,\ \text{response flexibility}\\
&= A,\ \text{action flexibility}\\
&= S,\ \text{state flexibility}
\end{aligned}
$$

Table 3 illustrates where each of these five flexibility dimensions is utilized, in terms of the level of requirements specification (α) and quantity of manufacturing system configurations

Table 3. Flexibility dimensions and their relationships to the level of requirements specification (α) and quantity of system configurations used (β_2).

α	$\beta_2 = 1$ (single system configuration), flexibility at a time	$\beta_2 > 1$ (multiple system configurations), flexibility over time
I	*Operational flexibility*: the ability to utilize the elements of a manufacturing system, in alternative ways, at a time	*Operational flexibility*: the ability to utilize the elements of a manufacturing system, in alternative ways, over time
		Range flexibility: the ability of a manufacturing system to adopt different configurations within the existing capability and capacity envelope
		Response flexibility: the ease of moving from one manufacturing system configuration to another, within the existing capability and capacity envelope
		Action flexibility: the ability to change the capability and capacity envelope of a manufacturing system and the ease with which such changes can be made
II	*Range flexibility*: the ability of a manufacturing system to be capable, at a time, for multiple production states	*Range flexibility*: the ability of a manufacturing system to be capable, over time, for multiple production states. The ability to reconfigure the system to be capable for multiple states
III	*Operational flexibility*: the static ability of a manufacturing system to perform a given transformation, in alternative ways, at a time	*Operational flexibility*: the static ability of a manufacturing system to perform a given transformation, in alternative ways, over time
		Response flexibility: same as at $\alpha = \mathrm{I}$
		Action flexibility: same as at $\alpha = \mathrm{I}$
	State flexibility: the extent to which a manufacturing system is capable, at a time, for multiple production states for which it is known to be capable	*State flexibility*: the extent to which a manufacturing system is capable, over time, for multiple production states for which it is known to be capable
IV	*Range flexibility*: the ability of a manufacturing system to be stable, at a time, for multiple production states	*Range flexibility*: the ability of a manufacturing system to be stable, over time, for multiple production states. The ability to reconfigure the system to be stable for multiple states
V	*Operational flexibility*: the dynamic ability of a manufacturing system to perform a given transformation, in alternative ways, at a time	*Operational flexibility*: the dynamic ability of a manufacturing system to perform a given transformation, in alternative ways, over time
		Response flexibility: same as at $\alpha = \mathrm{I}$
		Action flexibility: same as at $\alpha = \mathrm{I}$
	State flexibility: the extent to which a manufacturing system is stable, at a time, for multiple production states for which it is known to be stable	*State flexibility*: the extent to which a manufacturing system is stable, over time, for multiple production states for which it is known to be stable

employed over the time frame of interest (β_2). Note that the exact wording of the flexibility dimension varies with these attributes, even though the interpretation remains the same.

4.5. Flexibility measurement approach, υ

Once the flexibility dimension is established, it is natural to be concerned with the measurement approach employed. As evidenced by the literature, a large variety of flexibility measures have been proposed. Although many measures are unique in some manner, the vast majority are similar with respect to the approach they employ. Therefore, the measurement approach employed also can be used to classify different flexibility terms. As reported by Gerwin (1993), counting the number of options at a given point in time undoubtedly is the most common measurement approach in practice. Given N items, we can identify two such measurement approaches:

1. Flexibility is viewed in an absolute sense; that is, the more items that can be selected, the greater is the flexibility. In such cases, the measure will depend on the ability to select from all N items; that is, simply on the *quantity* of items (Q).
2. Flexibility is viewed in a relative sense; that is, we have some item we know can be selected, and the more items is the remaining group that can be selected, the greater is the flexibility. In such cases, flexibility will depend on the ability to select from the remaining $N-1$ items; that is, on the *relative quantity* of items (Q_{REL}). This is flexibility as the ability to cope with change.

The second approach to measuring flexibility is where we have a set of items that can be selected, and values indicating the desirability of the items. Based upon the entropic approach to flexibility measurement (Kumar and Kumar, 1987), four different types of measures can be identified:

1. Flexibility is viewed in an absolute sense; that is, the closer the items are together, the greater the flexibility. Flexibility thus depends simply on the *desirability* of the items (D). This is flexibility in terms of sensitivity to change.
2. Flexibility is viewed in a relative sense. We have some reference value, and the closer the remaining values are to the reference value, the greater is the flexibility. Flexibility thus depends on the *relative desirability* of the items (D_{REL}).
3. Flexibility again is viewed in an absolute sense, but we now have some criteria that allows us to establish whether we consider the item desirable or not. In this case, flexibility is reduced to a matter of quantity; and therefore the more items that satisfy the desirability constraint, the greater is the flexibility. Flexibility thus depends on the *constrained desirability* of the items (D^*).
4. Flexibility again is viewed in the relative sense and again some desirability criteria is present. In this case, the reference value must satisfy the desirability constraint: the more of the remaining values that also satisfy this constraint, the greater is the

flexibility. Flexibility thus depends on the *relative constrained desirability* of the items (D^*_{REL}).

Summarizing the preceding, the flexibility measurement approach can be specified as follows:

$$\begin{aligned}
\upsilon &= \text{flexibility measurement approach}\\
&= Q,\ \text{quantity of items}\\
&= Q_{\mathrm{REL}},\ \text{quantity of items relative to reference item}\\
&= D,\ \text{extent to which desirability of items close together}\\
&= D_{\mathrm{REL}},\ \text{extent to which desirability of items close to reference value}\\
&= D^*,\ \text{quantity of desirability values satisfying desirability constraint}\\
&= D^*_{\mathrm{REL}},\ \text{quantity of desirability values in addition to reference satisfying}\\
&\quad\ \text{desirability constraint}
\end{aligned}$$

It is important to note that though various measurement approaches can be utilized for different flexibility dimensions, the two attributes are not independent. Table 4 indicates which of the six measurement approaches apply to which flexibility dimensions. An example application also is presented for each combination to aid in understanding these relationships.

4.6. Time frame, τ

The last item used to specify the context in which flexibility is to be defined and measured is the time frame of interest. Two approaches to specifying the time domain can be found in the literature. The first is to specify absolute or relative time intervals. Gustavsson (1984) suggests three intervals: short, medium, and long. These same intervals also are advocated by Gupta and Buzacott (1989), who also suggest values: several minutes to several hours (short), several days to several months (medium), and several months to several years (long). Steinhilper (1985) classifies flexibilities as being either short term or long term; Slack (1987) also uses this distinction. Barad and Sipper (1988) categorize flexibility types as being short to medium term or long term.

The second approach is to specify the time frame in terms of the various decision-making activities required in manufacturing. For example, Gustavsson (1984), among others, suggests three levels: strategic, operational, and tactical. Strategic-level decisions are concerned with what is to be made (product definitions), aggregate production volumes, and changing the manufacturing system at the facility level (e.g., buy or install new equipment, rearrange existing equipment). Tactical-level decisions are concerned with what product mix to employ, production rates to use, and the like, as well as changing the manufacturing system at the group level (e.g., when to retool machines). Operational-level decisions are concerned with the real-time operation of a given system configuration for specified production requirements, as well as changing the manufacturing system at the equipment

Table 4. Possible flexibility dimensions (η) for each flexibility measurement approach (υ) and example applications.

	Flexibility dimension, η				
υ	O (Operational)	R (Range)	Re (Response)	A (Action)	S (State)
Q		x Ability to process different products		x Ability to change capability and capacity envelope	
Q_{REL}	x Quantity of routes for a given product	x Ability to cope with changes in given product(s)			
D			x Ease with which system configuration can be changed	x Ease with which changes to capability and capacity envelope can be made	x Extent to which performance changes with changing product mix
D_{REL}	x Desirability of each route for a given product		x Ease with which system configuration can be changed relative to a given change		x Extent to which performance changes with changes in a given product mix
D^*		x Ability to process different products efficiently		x Ability to easily change capability and capacity envelope	
D^*_{REL}	x Quantity of desirable routes for a given product	x Ability to cope efficiently with changes in given product(s)			

$\alpha/\beta/\gamma/\eta/\upsilon/\tau$ = flexibility type classification, where

α = level of manufacturing requirements specification
$\in \{\mathrm{I, II, III, IV, V}\}$

β = manufacturing system specification
$= \{\beta_1, \beta_2\}$
where β_1 = level of decomposition and scope of view of manufacturing system
$\in \{F, f, G, g, M, m\}$
β_2 = quantity of manufacturing system configurations over time frame
$\in \{1, n\}$

γ = manufacturing environment specification
$= \{\gamma_1 (\gamma_2)\colon \gamma_3, \gamma_4, \gamma_5\}$
where γ_1 = nature of environment
$\in \{P, \Delta P, \Delta I, \Delta S\}$
γ_2 = level of uncertainty associated with changes
$\in \{d, p\}$
$\gamma_3, \gamma_4, \gamma_5$ = type and quantity of changes defining given environment
$\in \{1, m, M, -\}$

η = flexibility dimension
$\in \{O, R, Re, A, S\}$

υ = flexibility measurement approach
$\in \{Q, Q_{\mathrm{REL}}, D, D_{\mathrm{REL}}, D^*, D^*_{\mathrm{REL}}\}$

τ = time frame
$\in \{T_{\mathrm{STR}}, T_{\mathrm{TAC}}, T_{\mathrm{OP}}\}$

Figure 2. Classification scheme for manufacturing flexibility terms.

level (e.g., change machine setup). This approach to specifying the time domain is preferred as (1) these terms indicate the role of a given flexibility term with regard to company operations and (2) actual interval times may vary from industry to industry. Therefore, we have

$$
\begin{aligned}
\tau &= \text{time frame} \\
&= T_{\mathrm{STR}},\ \text{strategic level} \\
&= T_{\mathrm{TAC}},\ \text{tactical level} \\
&= T_{\mathrm{OP}},\ \text{operational level}
\end{aligned}
$$

4.7. Summary of modeling framework and classification scheme

The classification scheme just presented is summarized in figure 2.

5. Example: Classification and analysis of some existing flexibility terms

To demonstrate the classification scheme, it was used to classify a large variety of flexibility terms found in the literature. These terms and their classifications are presented in Table 5. Similar flexibility terms are grouped together to aid in comparison. It should be stressed that the classifications may not be entirely accurate, as in many cases much of the information required to perform the classification was not given or subject to interpretation, requiring one or more assumptions to be made. This is detailed as follows:

- The level of manufacturing requirements specification α was not always apparent. For example, a definition such as "the ability to handle changes in the items being processed" could be at either $\alpha = \text{II}$ (i.e., ability of system to be capable for changes in product definitions or mix) or at $\alpha = \text{V}$ (i.e., ability of system to cope with changes in, say, production volume). The level to use in the classification then is entirely a matter of interpretation, based on the information available.
- The level of decomposition and scope of view for the manufacturing system, β_1, were not given in many instances; that is, the flexibility term could be for the entire manufacturing system, a given cell, all the machines in a given department, and so forth. In such cases, the highest level of system specification, that is, $\beta_1 = F$, was assumed. The relative quantity of system configurations allowed, β_2, also was not always clear. If any mention was made of the flexibility term as relating to flexibility over time, $\beta_2 = n$. Otherwise, it was assumed that the term referred to flexibility at a time and hence $\beta_2 = 1$.
- The level of uncertainty associated with changes in the manufacturing environment, γ_2, was not always specified. Changes were assumed to be deterministic, that is, $\gamma_2 = d$, in such cases. It appears that very few researchers address this attribute in developing flexibility terms. Additionally, the relative quantity of changes being considered for a given environment, $\gamma_i,\ i = 3,\ 4,\ 5$, was not always clear. Phrases such as "all possible products" or "universe of possible products" indicated the universe of all possible changes was being considered ($\gamma_i = M$), whereas, "number of different products," "given set of part types," or "defined portfolio of products" indicated that a restricted set of changes was assumed ($\gamma_i = m$). In cases where the relative quantity of changes could not be established, a restricted set of changes was assumed.

Analysis of the flexibility terms and their corresponding classifications can be performed in two ways. The first is analysis of individual terms. Three observations can be made in this regard. The first observation is that many terms lack sufficient information to conclusively establish the classification, as discussed previously. The second is that several flexibility terms allow for a very broad interpretation and hence a large variety of possible classifications: such terms include *adaptation flexibility* and *application flexibility* (Zelenovic, 1982), *market flexibility* (Sethi and Sethi, 1990), and *parts manufacturing flexibility* (Frazelle, 1986). One way to interpret this is that such terms are at the top of a flexibility hierarchy and so depend on a large variety of lower-level terms (see, for example, the flexibility hierarchy of Sethi and Sethi, 1990). The third observation is that multiple classifications can be identified for many terms, including *design change flexibility* (Frazelle, 1986), *expansion flexibility* and *routing flexibility* (Browne et al., 1984), *machine flexibility* and *mix flexibility*

Table 5. Flexibility terms and classifications.

Flexibility term	Reference	Classification						
		α	$/\beta_1, \beta_2$ /	$\gamma_1(\gamma_2) : \gamma_3, \gamma_4, \gamma_5$	$/\eta/$	υ	/	τ
Adaptation	Zelenovic (1982)	I	$/F,\ n$ /		$/O/$	D_{REL}	/	$T_{\text{TAC[OP]}}$
		I	$/F,\ n$ /		$/Re/$	D	/	$T_{\text{TAC[OP]}}$
Application	Zelenovic (1982)	II	$/F,\ 1$ /	?	$/R/$	Q	/	$T_{\text{TAC[STR]}}$
		IV	$/F,\ 1$ /	?	$/R/$	Q	/	$T_{\text{TAC[STR]}}$
Changeover	Gerwin (1987)	II	$/F,\ n$ /	$\Delta P(d) : —, m, —$	$/R/$	Q_{REL}	/	T_{TAC}
Demand	Gustavsson (1984)	IV	$/F,\ 1$ /	$\Delta P(p) : —, —, m$	$/R/$	Q	/	T_{TAC}
Design change	Gerwin (1982)	II	$/F,\ n$ /	$\Delta P(d) : m, —, —$	$/R/$	D^*_{REL}	/	T_{STR}
	Frazelle (1986)	II	$/F,\ 1[n]$ /	$P : 1, —, —$	$/R/$	D^*	/	T_{TAC}
Expansion	Browne et al. (1984)	I	$/F,\ n$ /		$/A/$	Q	/	T_{STR}
		I	$/F,\ n$ /		$/A/$	D^*	/	T_{STR}
	Sethi and Sethi (1990)	I	$/F,\ n$ /		$/A/$	D	/	T_{STR}
	Carter (1986)	I	$/F,\ n$ /		$/A/$	Q	/	T_{STR}
Input	Tarondeau (1986)	I	$/M,\ n$ /		$/O/$	Q_{REL}	/	T_{OP}
Job	Buzacott (1982)	II	$/F,\ 1$ /	$\Delta P(p) : m, —, —$	$/R/$	Q_{REL}	/	T_{TAC}
Machine	Buzacott (1982)	V	$/f,\ 1$ /	$\Delta S(d) : m$	$/S/$	D	/	T_{OP}
	Carter (1986)	I	$/M,\ 1[n]/$		$/O/$	Q_{REL}	/	T_{OP}
		I	$/M,\ 1[n]/$		$/Re/$	D	/	T_{OP}
	Taymaz (1989)	I	$/M,\ n$ /		$/Re/$	D	/	T_{OP}
	Sethi and Sethi (1990)	I	$/m,\ n$ /		$/O/$	D^*_{REL}	/	T_{OP}
	Chandra and Tombak (1992)	I	$/m,\ 1$ /		$/Re/$	D	/	T_{OP}
	Browne et al. (1984)	III	$/M,\ n$ /	$\Delta P(d) : —, m, —$	$/Re/$	D_{REL}	/	T_{OP}
Market	Sethi and Sethi (1990)	III	$/F,\ 1$ /	$\Delta P(d) : [\text{any}]$	$/Re/$	D	/	T_{STR}
		V	$/F,\ 1$ /	$\Delta P(d) : [\text{any}]$	$/Re/$	D	/	T_{STR}
Material	Gerwin (1987)	I	$/M,\ n$ /		$/O/$	Q_{REL}	/	T_{OP}
		III	$/M,\ n$ /	$\Delta I(d) : m, —$	$/S/$	D	/	T_{OP}
Material handling	Chaterjee, Cohen, and Maxwell (1987)	I	$/f,\ n$ /		$/O/$	Q_{REL}	/	T_{OP}
	Sethi and Sethi (1990)	II	$/f,\ 1$ /	$\Delta P(d) : M, —, —$	$/R/$	D^*	/	T_{OP}
Mix	Gerwin (1982, 1987)	II	$/F,\ 1$ /	$\Delta P(d) : —, m, —$	$/R/$	Q	/	T_{TAC}
	Carter (1986)	IV	$/F,\ 1$ /	$\Delta P(d) : m, —, 1$	$/R/$	Q	/	T_{STR}
		IV	$/F,\ 1$ /	$\Delta P(d) : —, m, 1$	$/R/$	D^*	/	T_{TAC}
		V	$/F,\ 1$ /	$\Delta P(d) : —, m, 1$	$/Re/$	D	/	T_{TAC}

(*Continued on next page.*)

Table 5. (*Continued.*)

Flexibility term	Reference	Classification						
		α	$/\beta_1, \beta_2$ /	$\gamma_1(\gamma_2):\gamma_3, \gamma_4, \gamma_5$	$/\eta/$	υ	/	τ
Mix-change	Carter (1986)	IV	$/F,\ 1$ /	$\Delta P(d):—, M, 1$	$/R/$	D^*	/	T_{OP}
Modification	Gerwin (1987)	II	$/f,\ 1$ /	$\Delta P(d):m, —, —$	$/R/$	Q	/	T_{TAC}
Operation	Browne et al. (1984)	III	$/f,\ 1$ /	$P:1, —, —$	$/O/$	Q_{REL}	/	T_{OP}
	Sethi and Sethi (1990)	III	$/F,\ 1$ /	$P:1, —, —$	$/O/$	Q_{REL}	/	T_{OP}
Operational	Chryssolouris and Lee (1992)	V	$/F,\ n$ /	$\Delta P(p):—, 1, m$	$/Re/$	D	/	T_{STR}
Parts	Gerwin (1982)	II	$/F,\ n$ /	$\Delta P(d):m, —, —$	$/R/$	Q	/	T_{STR}
Parts manufacturing	Frazelle (1986)	II	$/F,\ 1[n]/$	$\Delta P(d):$[any]	$/R/$	D^*	/	[any]
		IV	$/F,\ 1[n]/$	$\Delta P(d):$[any]	$/R/$	D^*	/	[any]
Process	Browne et al. (1984)	III	$/f,\ 1$ /	$P:—, 1, —$	$/O/$	Q_{REL}	/	T_{OP}
	Jaikumar (1984)	III	$/G,\ 1$ /	$P:1, —, —$	$/O/$	Q_{REL}	/	T_{OP}
		III	$/G,\ 1$ /	$P:1, —, —$	$/O/$	D_{REL}	/	T_{OP}
	Sethi and Sethi (1990)	II	$/F, 1$ /	$\Delta P(d):M, —, —$	$/R/$	D^*	/	T_{OP}
Product	Browne et al. (1984)	II	$/F, 1$ /	$\Delta P(d):—, m, —$	$/R/$	D^*	/	T_{TAC}
	Gustavsson (1984)	II	$/F, 1$ /	$\Delta P(p):M, —, —$	$/R/$	Q_{REL}	/	T_{STR}
	Jaikumar (1984)	II	$/F, n$ /	$\Delta P(p):m, —, —$	$/R/$	Q	/	T_{STR}
	Sethi and Sethi (1990)	III	$/F, 1$ /	$\Delta P(d):M, —, —$	$/Re/$	D_{REL}	/	T_{STR}
	Chryssolouris and Lee (1992)	II	$/F, 1$ /	$\Delta P(p):m, —, —$	$/R/$	Q	/	T_{TAC}
		III	$/F, 1$ /	$\Delta P(p):m, —, —$	$/Re/$	D	/	T_{TAC}
Product mix	Frazelle (1986)	II	$/F, 1$ /	$\Delta P(d):—, m, —$	$/R/$	Q	/	T_{TAC}
Production	Browne et al. (1984)	II	$/G,\ n$ /	$\Delta P(d):M, —, —$	$/R/$	Q	/	T_{STR}
	Carter (1986)	I	$/F, 1$ /		$/R/$	Q	/	T_{TAC}
	Sethi and Sethi (1990)	II	$/F, 1$ /	$\Delta P(d):M, —, —$	$/R/$	D^*	/	T_{STR}
Program	Sethi and Sethi (1990)	IV	$/F, 1$ /	$\Delta S(d):M$	$/R/$	Q	/	T_{OP}
	Jaikumar (1984)	IV	$/G, 1$ /	$\Delta S(d):m$	$/R/$	Q	/	T_{OP}
Rerouting	Gerwin (1987)	III	$/f, 1$ /	$P:1, —, —$	$/O/$	Q_{REL}	/	T_{OP}
		III	$/f, 1$ /	$\Delta S(d):m$	$/S/$	D	/	T_{OP}
Routing	Gerwin (1982)	V	$/F, 1$ /	$P:1, —, 1$	$/O/$	Q_{REL}	/	T_{OP}
	Browne et al. (1984)	III	$/F, 1$ /	$P:1, —, —$	$/O/$	Q_{REL}	/	T_{OP}
		V	$/G, 1$ /	$\Delta S(d):m$	$/S/$	D	/	T_{OP}
	Carter (1986)	I	$/f, 1$ /		$/O/$	Q_{REL}	/	T_{OP}
	Frazelle (1986)	II	$/F, 1$ /	$P:1, —, —$	$/R/$	D^*	/	T_{OP}
	Chung and Chen (1989)	III	$/f, 1$ /	$P:1, —, —$	$/O/$	Q_{REL}	/	T_{OP}

(*Continued on next page.*)

Table 5. (*Continued.*)

Flexibility term	Reference	Classification α	$/\beta_1, \beta_2/$	$\gamma_1(\gamma_2) : \gamma_3, \gamma_4, \gamma_5$	$/\eta/$	υ	/	τ
	Sethi and Sethi (1990)	III	$/F, 1$ /	$P : 1, —, —$	$/O/$	Q_{REL}	/	T_{OP}
	Chandra and Tombak (1992)	III	$/f, 1$ /	$P : 1, —, —$	$/O/$	Q_{REL}	/	T_{OP}
		III	$/f, 1$ /	$P : 1, —, —$	$/O/$	D_{REL}	/	T_{OP}
Sequencing	Gerwin (1987)	I	$/f, 1$ /		$/O/$	Q_{REL}	/	T_{TAC}
Total system	Chung and Chen (1989)	III	$/F, 1$ /	$\Delta P(d) : m, —, —$	$/Re/$	D	/	T_{STR}
		V	$/F, 1$ /	$\Delta P(d) : 1, —, m$	$/Re/$	D	/	T_{TAC}
Volume	Gerwin (1982, 1987)	IV	$/F, 1$ /	$\Delta P(d) : 1, —, m$	$/R/$	Q_{REL}	/	T_{TAC}
	Browne et al. (1984)	IV	$/G, 1$ /	$\Delta P(d) : 1, —, m$	$/R/$	D^*	/	T_{TAC}
	Frazelle (1986)	II	$/F, 1$ /	$\Delta P(d) : 1, —, m$	$/R/$	Q	/	T_{OP}
	Taymaz (1986)	V	$/M, 1$ /	$\Delta P(d) : 1, —, m$	$/S/$	D	/	T_{OP}
	Sethi and Sethi (1990)	IV	$/F, 1$ /	$\Delta P(d) : 1, —, M$	$/R/$	D^*	/	T_{STR}

(Carter, 1986), *material flexibility* and *rerouting flexibility* (Gerwin, 1987), *process flexibility* (Jaikumar, 1984), *product flexibility* (Chryssolouris and Lee, 1992), and *total system flexibility* (Chung and Chen, 1989). In each case, what is considered to be a single flexibility term in fact appears to be a composite item, based on the classification analysis. Whether consciously or not, it appears that many researchers incorporate multiple flexibilities into a single term to capture the essence of what they consider to be a certain type of flexibility.

The second type of analysis consists of comparing the various terms with one another to determine if terms having the same name in fact refer to the same type of flexibility or not. The following identical terms have the exact same classification:

- *expansion flexibility*: Browne et al. (1984) and Carter (1986).
- *machine flexibility*: Carter (1986) and Taymaz (1989).
- *routing flexibility*: Chung and Chen (1989) and Chandra and Tombak (1992).
- *routing flexibility* (different classification): Browne et al. (1984) and Sethi and Sethi (1990).

Therefore, we can say, for example, that Carter's machine flexibility appears to be highly similar to that of Taymaz (we cannot say they are identical without comparing the actual terms). The lack of a large quantity of matches between identical terms at first appears to be in disagreement with published literature (e.g., Gupta and Goyal, 1989; Correa, 1994), which shows matches between many flexibility terms developed by various researchers. This easily can be explained, however, in that comparison via the proposed classification scheme affords much higher resolution: terms that on initial analysis appear to be the same in fact are different when examined at a greater level of detail. Identical terms that appear to be very nearly the same (α identical, mismatch between one or two other attributes only) include the following:

- *operation flexibility*: Browne et al. (1984) and Sethi and Sethi (1990).
- *product flexibility*: Gustavsson (1984) and Jaikumar (1984).
- *product flexibility* (different classification): Sethi and Sethi (1990) and Chryssolouris and Lee (1992).
- *production flexibility*: Browne et al. (1984) and Sethi and Sethi (1990).
- *program flexibility*: Jaikumar (1984) and Sethi and Sethi (1990).
- *volume flexibility*: Browne et al. (1984), Gerwin (1987), and Sethi and Sethi (1990).

The classifications then indicate, for example, that Jaikumar's product flexibility is quite similar to that of Gustavsson. Finally, the classifications also indicate identical terms that appear to be very different in meaning. Such terms include

- *machine flexibility*: Browne et al. (1984) and Carter (1986).
- *mix flexibility*: Carter (1986) and Gerwin (1987).
- *routing flexibility*: Gerwin (1982) and Carter (1986).
- *volume flexibility*: Frazelle (1986) and Taymaz (1989).

So, for example, Carter's routing flexibility appears to be quite different from that of Gerwin. That the vast majority of identical flexibility terms are quite different, on detailed analysis, is not surprising when one considers that the different terms were developed based on differing views of what constitutes a manufacturing system, its environment, and what attributes are necessary to define *flexibility*. Utilization of the framework proposed in this work should help alleviate this problem.

6. Conclusions

A framework for defining manufacturing flexibility types and measures, and a corresponding classification scheme, have been proposed. These were developed based on a well-defined model of the manufacturing system and its environment. The utility of these items is that they can (1) serve as a guide to researchers in developing new flexibility terms by indicating what attributes should be specified and (2) assist in evaluating existing terms to see the extent to which they are similar. Based on the example presented, two important conclusions can be drawn. The first is that, in the absence of a suitable framework, flexibility terms will be defined in different ways and to different degrees, making classification (and subsequent analysis) difficult. The second is that comparison of flexibility terms based on their classification is a quick and easy way to establish the extent to which identical names refer to the same flexibility type (and possibly measure) and, if not, the manner in which the terms differ.

In developing any modeling framework and classification scheme, trade-offs undoubtedly will occur between tractability (ease of use) and validity. The subject of flexibility modeling, definition, and measurement has proven to be sufficiently difficult that any framework or classification scheme of low validity undoubtedly will be of limited value. Therefore, validity was emphasized in developing the framework and classification scheme, and consequently these items at first appear to be quite complex. In fact, however, they are relatively straightforward to use after one has become familiar with their structure and manner of implementation.

Finally, it should be pointed out that one thing the proposed framework for defining flexibility terms cannot be used for is identifying all of the various flexibilities found in manufacturing. To do this in a structured manner, one must start with suitable models and then *derive* the various flexibility types, based on the elements composing these models and their relationships with one another. The framework nonetheless is of value for this pursuit in that it helps us determine what we are looking for.

Continued research is required to develop a methodology for deriving flexibility types from suitable models as described here. We hope that the framework and classification scheme proposed here will prove to be of value in performing this difficult task.

Note

1. Note that these terms are not the same as *flexibility at times* and *flexibility over time* as proposed by Yilmaz and Davis (1987).

References

Barad, M. and Sipper, D., “Flexibility in Manufacturing Systems: Definitions and Petri Net Modeling,” *International Journal of Production Research*, Vol. 26, No. 2, pp. 237–248 (1988).

Benjaafar, S., “Modeling and Analysis of Flexibility in Manufacturing Systems,” Ph.D. dissertation, School of Industrial Engineering, Purdue University, West Lafayette, IN (1992).

Brill, P.H. and Mandelbaum, M., “On Measures of Flexibility in Manufacturing Systems,” *International Journal of Production Research*, Vol. 27, No. 5, pp. 747–756 (1989).

Browne, J., Dubois, D., Rathmill, K., Sethi, S.P., and Stecke, K.E., “Classification of Flexible Manufacturing Systems,” *FMS Magazine*, pp. 114–117 (April 1984).

Burbidge, J.L., *The Introduction of Group Technology*, John Wiley & Sons, New York (1975).

Buzacott, J.A., “The Fundamental Principles of Flexibility in Manufacturing Systems,” *Flexible Manufacturing Systems, Proceedings of First International Conference* (Brighton, UK), North-Holland, Amsterdam, The Netherlands, pp. 23–30 (October 1982).

Carter, M.F., “Designing Flexibility into Automated Manufacturing Systems,” *Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems* (Ann Arbor, MI), K.E. Stecke and R. Suri (Eds.), Elsevier Science Publishers, B.V., Amsterdam, The Netherlands, pp. 107–118 (August 1986).

Chandra, P. and Tombak, M.M., “Models for the Evaluation of Routing and Machine Flexibility,” *European Journal of Operational Research*, Vol. 60, pp. 156–165 (1992).

Chatterjee, A., Cohen, M.A., and Maxwell, W.L., “A Planning Framework for Flexible Manufacturing Systems,” WP #87-07-04, University of Pennsylvania, Philadelphia (July 1987).

Chryssolouris, G. and Lee, M., “An Assessment of Flexibility in Manufacturing Systems,” *Manufacturing Review*, Vol. 5, No. 2, pp. 105–116 (June 1992).

Chung, C.H. and Chen, I.J., “A Systematic Assessment of the Value of Flexibility for an FMS,” *Proceedings of the Third ORSA/TIMS Conference on Flexible Manufacturing Systems* (Cambridge, MA), K.E. Stecke and R. Suri (Eds.), Elsevier Science Publishers, B.V., Amsterdam, The Netherlands, pp. 27–34 (August 1989).

Correa, H.L., *Linking Flexibility, Uncertainty, and Variability in Manufacturing Systems*, Ashgate Publishing Co., Aldershot, England (1994).

Dooner, M. and De Silva, A., “Conceptual Modeling to Evaluate the Flexibility Characteristics of Manufacturing Cell Designs,” *Proceedings of the 28th Matador Conference*, UMIST, Manchester, United Kingdom (1990).

Frazelle, E.H., “Flexibility: A Strategic Response in Changing Times,” *Industrial Engineering*, pp. 17–20 (March 1986).

Gerwin, D., “Do’s and Don’ts of Computerized Manufacturing,” *Harvard Business Review*, Vol. 60, pp. 107–116 (March–April 1982).

Gerwin, D., "An Agenda for Research on the Flexibility of Manufacturing Processes," *International Journal of Operations and Production Management*, Vol. 7, No. 1, pp. 38–49 (1987).

Gerwin, D., "Manufacturing Flexibility: A Strategic Perspective," *Management Science*, Vol. 39, No. 4, pp. 395–410 (1993).

Goldhar, J.D. and Jelinek, M., "Plan for Economies of Scope," *Harvard Business Review*, Vol. 61, pp. 141–148 (November–December 1983).

Gupta, D. and Buzacott, J.A., "A Framework for Understanding Flexibility of Manufacturing Systems," *Journal of Manufacturing Systems*, Vol. 8, No. 2, pp. 89–97 (1989).

Gupta, Y.P. and Goyal, S., "Flexibility of Manufacturing Systems: Concepts and Measurements," *European Journal of Operational Research*, Vol. 43, pp. 119–135 (1989).

Gustavsson, S., "Flexibility and Productivity in Complex Production Processes," *International Journal of Production Research*, Vol. 22, No. 5, pp. 801–808 (1984).

Jaikumar, R., "Flexible Manufacturing Systems: A Managerial Perspective," WP #1-784-078, Harvard Business School, Boston (January 1984).

Jones, A.T. and McLean, C.R., "A Proposed Hierarchical Control Model for Automated Manufacturing Systems," *Journal of Manufacturing Systems*, Vol. 5, No. 1, pp. 15–25 (January 1986).

Kumar, V. and Kumar, U., "Manufacturing Flexibility: A New Approach to Its Measurement," *IIE International Industrial Engineering Conference Proceedings*, pp. 469–475 (1987).

Lawler, E.L., Lenstra, J.K., Rinnooy Kan, A.H.G., and Shmoys, D.B., "Sequencing and Scheduling: Algorithms and Complexity," in *Handbooks in Operations Research and Management Science*, Vol. 4, *Logistics of Production and Inventory*, S.C. Graves, A.H.G. Rinnooy Kan, and P. Zipkin (Eds.), North-Holland, Amsterdam, The Netherlands (1990).

Mandelbaum, M., "Flexibility in Decision Making: An Exploration and Unification." Ph.D. thesis, Department of Industrial Engineering, University of Toronto, Toronto, Canada (1978).

Pyoun, Y.S. and Choi, B.K., "Quantifying the Flexibility Value in Automated Manufacturing Systems," *Journal of Manufacturing Systems*, Vol. 13, No. 2, pp. 108–118 (1994).

Sethi, A.K. and Sethi, S.P., "Flexibility in Manufacturing: A Survey," *International Journal of Flexible Manufacturing Systems*, Vol. 2, pp. 289–328 (1990).

Shewchuk, J.P., "A Systems Approach to Flexibility and Manufacturing Systems Analysis and Design," Ph.D. dissertation, School of Industrial Engineering, Purdue University, West Lafayette, IN (1995).

Shewchuk, J.P. and Moodie, C.L., "A Framework for Classifying Flexibility Types in Manufacturing," *Computers in Industry*, Vol. 33, Nos. 2–3, pp. 261–270 (1997).

Slack, N., "The Flexibility of Manufacturing Systems," *International Journal of Operations and Production Management*, Vol. 7, No. 4, pp. 35–45 (1987).

Son, Y.K. and Park, C.S., "Economic Measure of Productivity, Quality and Flexibility in Advanced Manufacturing Systems," *Journal of Manufacturing Systems*, Vol. 6, No. 3, pp. 193–207 (1987).

Stecke, K.E. and Raman, N., "Production Flexibilities and Their Impact on Manufacturing Strategy," WP #484, Graduate School of Business Administration, University of Michigan (1986).

Steinhilper, R., "Recommendations for FMS Planning and Realization," in *Flexible Manufacturing Systems*, H.J. Warnecke and R. Steinhilper (Eds.), Springer-Verlag, Berlin, pp. 87–97 (1985).

Tarondeau, J.C., "Technologies Flexibles et Performances," Working paper, ESSEC, Cergy, France (1986).

Taymaz, E., "Types of Flexibility in Single-Machine Production System," *International Journal of Production Research*, Vol. 27, No. 11, pp. 1891–1899 (1989).

Tombak, M.M., "The Importance of Flexibility in Manufacturing," Working Paper, European Institute of Business Administration (INSEAD), Fontainebleau, France (1988).

Wu, B., *Manufacturing Systems Design and Analysis*, Chapman and Hall, New York, NY, pp. 28–69, 151–183 (1992).

Yilmaz, O.S. and Davis, R.P., "Flexible Manufacturing Systems: Characteristics and Assessments," *Engineering Management International*, Vol. 4, No. 3, pp. 209–212 (1987).

Zelenovic, D.M., "Flexibility—A Condition for Effective Production Systems," *International Journal of Production Research*, Vol. 20, No. 3, pp. 319–337 (1982).