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Int. J. Production Economics 86 (2003) 47–62
international journal of production economics
www.elsevier.com/locate/dsw

Analysis of the structural measures of flexibility and agility using a measurement theoretical framework ☆

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Received 29 June 2001; accepted 3 November 2002

Abstract

Manufacturing firms have great interest in developing flexible and agile manufacturing systems. These manufacturing system strategies seek to leverage the inherent properties of the technologies and systems for competitive advantage. Measurement has always played a role in planning and managing these complex systems. Most measurement systems concentrate on operational measures of the system, however, many of the manufacturing strategies are based on structural properties embodied in the system architecture, technology resources, and system control policies. We present a measurement framework to analyze measures of structural properties of the enterprise system. The measurement framework provides a mathematical foundation for formalizing our intuition of what constitutes a measure. Our analysis reveals undesirable properties of some measures, mainly because they are developed without any formal basis. The measurement framework can provide a consistent basis for specifying and using measures, which will empower system designers to better incorporate desirable structural properties to align system design with enterprise strategy.

Keywords: Structural measures; Flexibility; Agility; Supply chains; Metrics

1. Introduction

Manufacturing enterprises have long recognized the desirability of certain system properties such as flexibility and agility for potential competitive advantage. Enterprises with these properties are more able to cope with increased environmental uncertainty, adapt to the faster pace of change of today's markets, and react within the smaller windows of opportunity for decision-making. The strategic decision makers must determine which properties the systems must exhibit, to what level the system requires those properties, and how best to incorporate those properties into the system.

The aforementioned properties, called *structural properties,* are designed into the system architecture, operating policies, technologies, and organizations. Buzacott (1999) says structure is one of the classical issues to be addressed in manufacturing strategy. He defines structure as how individual system components relate to each other and how the relationships determine overall system

☆ This research is partially supported by research grant DMI 0075395 from the National Science Foundation.
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0925-5273/03/$ - see front matter
doi:10.1016/S0925-5273(03)00004-5

behavior. Three types of significant relationships are the material and information flows between the system components, the organizational relationships, and the communication network connecting people with people or machines. Other researchers also mention structural properties, albeit with different terminology. Chryssolouris and Lee (1992) recognize two views of flexibility, the first is where flexibility is an "intrinsic attribute" of the manufacturing system and the second is a "relative attribute" that depends on external demands placed on the system. Shewchuk and Moodie (1998) also find that many flexibility measures are inherent properties of the system and can be determined with no reference to any particular production requirements. Indeed, Taymaz (1989) says machine, routing, and control flexibility are defined without reference to production characteristics (product mix, production runs, etc.) and they are determined a priori by design. Collectively, these authors are all referring to structural properties of the manufacturing system.

Most measurement systems concentrate on operational measures. *Operational measures* are of the enterprise's operation in respect to its environment and can change dramatically in short periods of time. The Balanced Scorecard (Kaplan and Norton, 1992) uses financial and non-financial operational measures to manage enterprise strategy. Neely et al. (1997) present a structured performance measurement approach to defining measures, their purpose, and how they relate to management objectives. Suwignjo et al. (2000) and Bititci et al. (2001) utilize the analytical hierarchy process to measure performance. These measurement models of operational measures adhere to a decision theoretical framework such that they identify many factors, elicit a quantification from the decision maker (management), and then aggregate the many factors into an overall score. Decision theoretical approaches do not directly measure whether systems are flexible, agile, etc. because they measure past outcomes (by linking factors to performance) and cannot say to what degree a system posses a structural property.

To illustrate the difference between structural and operational measures consider an automobile. The engine can be measured in terms of the number of cylinders and each cylinder in liters. These are structural properties of the automobile; i.e. they are designed into the automobile. Operational performance measures of the automobile such as maximum speed attainable and gas mileage depend not only on the inherent properties of the automobile (number of cylinders and size) but also on operating characteristics such as air/fuel mix, fuel type, and others. Both structural characteristics and operational characteristics are important to the performance of the automobile, however, how they are used are different. Structural characteristics are designed into the system; afterwards they are difficult to change. Operational characteristics can be changed in the short term.

In the manufacturing literature there are a large number of measures for flexibility (Gupta and Goyal, 1989; Sethi and Sethi, 1990) and agility (Dove, 1994; Goranson, 2000). The large number of measures can lead to confusion since how does one select which measures to use. Moreover, sometimes different measures that purport to measure the same system property may actually conflict. Many measures of enterprise properties are vaguely worded and not quantified which means they cannot be consistently utilized in formulating and measuring strategic objectives. Overall, measures are often ambiguous, conflicting, and in some regard arbitrary. This issue has lead, for example, Shewchuk and Moodie (1998) to propose a taxonomy to classify all of the various flexibility types recorded in the literature. When considering flexibility measurement De Toni and Tonchia (1998) state, "Notwithstanding the importance and constant interest raised by flexibility in academia and managerial circles, the measure of flexibility is still an underdeveloped subject" (p. 1605).

The issues in utilizing measurement to design and manage enterprise systems are: (1) identifying structural properties and differentiate them from operational measures of the system, (2) overcoming ambiguous and often conflicting definitions by developing rigorous and formal definitions of the system properties and (3) establishing mathematical properties of the measure to correctly represent our understanding of the system property being measured and to exhibit properties considered essential for a proper measure. In this paper, we argue these problems can be alleviated through application of a measurement framework for structural properties derived from relational measurement theory. Measurement theory provides a formal mathematical basis so that measures that adhere to the framework exhibit desired properties and preserve relationships found in the empirical system (Krantz et al., 1971; Narens, 1985; Díez, 1997). Application of measurement theory allows us to precisely express system properties, map them into numerical values, utilize the full range of mathematical tools for validation, and to show us which statistical analyses are meaningful. Through the application of measurement theory we seek to avoid the undesirable results of informal and sometimes arbitrary assignment of numbers as proposed by many measures. Measurement theory is an appropriate approach for measuring structural properties because they are inherent characteristics of the system. Thus, we can model the system components and relationships in order to emphasize the particular structural property of interest and then measure it directly from the model. As a structural property it does not depend on external environmental conditions. For example, a machine has a structural property of how many different operations it can perform. The measure is independent of external factors such as feed rate, speed, part material, or location in the facility. The measurement frameworks of Suwignjo et al. (2000) and others are intended for operational measures and use a decision theoretical approach. This is because the assignment of a number to the property is somewhat subjective and they seek to aggregate many subfactors into a performance measure. For the machine flexibility structural property mentioned above there is a single number for the property (when properly modeled and measured according to measurement theory). The structural measure values could be used as input to the aggregation phase of the operational measurement methodologies, but actual definition, modeling, and measurement of the property is more appropriately done according to measurement theory.

In this paper, we first present relationship measurement theory and our development of a measurement framework for evaluating manufacturing enterprise system measures. Then we analyze different measures proposed in the literature with respect to the measurement framework. Our goal is to demonstrate how application of measurement theory can be applied to better define structural properties of enterprises and then monitor the enterprise as part of the enterprise strategy.

2. Relational measurement theory

Measurement is the assignment of numbers to attributes of an artifact according to some procedure so that certain properties and relationships are preserved (Krantz et al., 1971; Narens, 1985; Díez, 1997). Measurement starts with the definition of a system of interest, called the empirical system. An empirical system E is defined as the couple $(O, \succeq)$, where O is a set of objects in the system and $\succeq$ is a set of qualitative relationships between those objects. Even for simple empirical systems careful definition of the system is necessary. Consider measuring machine flexibility defined as the number of operations a machine can perform without expensive switching costs (Sethi and Sethi, 1990). There are many issues that must be clearly resolved. How do you define operations? Are operations as defined on a process plan or are they manufacturing features the machine can produce? Also, how do you define switching costs? Enterprise systems and their attributes are far more complex and less well understood. Consequently, definition of the attributes and relationships of the enterprise system is very important before measurement can proceed. Assuming definition of the empirical system the next step is to define a numerical or formal representational model. Let N be a set of numbers and $\geq$ be a set of quantitative relations then the formal representational model Z is $(N, \geq)$. The representation condition of measurement theory, shown in Fig. 1, states that there is a mapping m from O in the empirical system to N in the formal representational model such that $\succeq$ maps into $\geq$.

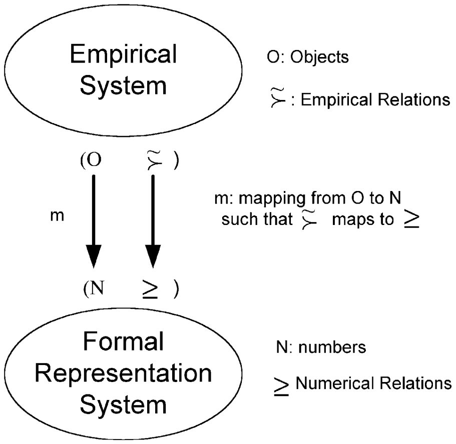

Fig. 1. Representation condition of measurement theory.

Definition 1 (Measure m). A measure m is a mapping m: $O \rightarrow N$ such that there exists for every empirical object $o \in O$ a formal object (measurement value) $m(o) \in N$.

The mapping must obey the representation condition. Formally the representation condition states:

$$x \succ y \Leftrightarrow m(x) \geq m(y). \tag{1}$$

As an example if in the empirical system there is the set O of machines and the relation R called "has more operations than" then a measure m will map O into a real number N and the relation $\succeq$ will be mapped into the quantitative relation $\geq$. m obeys the representation condition if and only if machine A has more operations than machine B when $m(A) \geq m(B)$. An issue, non-trivial, is of course finding an appropriate m that preserves the observed relations in the empirical model.

Measurement theory includes the concept of scales. The understanding of the empirical system leads to different scale types. In order of sophistication the scales are nominal, ordinal, interval, ratio, and absolute. The nominal scale is simply a categorization and is not considered here. Starting with the ordinal scale we define the scale and axioms.

Definition 2 (Ordinal scale). The system $(O, \succeq)$ is an ordinal scale when it is a weak order, which is transitive and complete.

Axiom 2.1: Transitive axiom states that if $o_1 \succcurlyeq o_2$ and $o_2 \succcurlyeq o_3 \Rightarrow o_1 \succcurlyeq o_3$.

Axiom 2.2: Complete axiom states that either $o_1 \succcurlyeq o_2$ or $o_2 \succcurlyeq o_1$.

Definition 3 (Interval scale). The interval scale is defined by an algebraic difference structure in which the differences between objects have meaning. $(O \times O, \succcurlyeq)$ is an algebraic difference structure if and only if the following axioms hold:

Axiom 3.1: The system $(O \times O, \succcurlyeq)$ is a weak order.

Axiom 3.2: If $(o_1 - o_2) \succcurlyeq (o_3 - o_4) \Rightarrow (o_4 - o_3) \succcurlyeq (o_2 - o_1)$.

Axiom 3.3: If $(o_1 - o_2) \succcurlyeq (o_1' - o_2')$ and $(o_3 - o_4) \succcurlyeq (o_3' - o_4') \Rightarrow (o_1 - o_3) \succcurlyeq (o_1' - o_3')$.

The ratio scale has a meaningful zero element and a unit such that the ratio between values is meaningful. There are two types of ratio scales, a non-additive ratio scale and an additive ratio scale. An additive ratio scale is defined with an extensive structure, which is the triple $(O, \succcurlyeq, o)$ (Krantz et al., 1971). The binary concatenation operator $\circ$ is defined as

Definition 4 (Concatenation operator). A closed binary or concatenation operator of objects $o_1, o_2 \in O$ such that for the closed binary or concatenation operator $\circ$ the object $o_1 \circ o_2 \in O$ is obtained by concatenating or composing o_1 and o_2 in a prescribed manner. The concatenation operator $\circ$ maps $O \times O$ into O.

The additive ratio scale is defined with the extensive structure.

Definition 5 (Additive ratio scale with extensive structure). The empirical system $(O, \gtrsim, \mathrm{o})$ is an Extensive Structure which forms a ratio scale if and only if the axioms 5.1 through 5.5 hold for all $o_1, \ldots, o_n$ in O. When the concatenation operator maps into addition $(+)$ in the numerical system then we call it an additive structure. This is the most common extensive structure found in physical measurement. The additive extensive structure is defined by axioms 5.1–5.5.

Axiom 5.1: $(O, \succeq)$ is a weak order.

Axiom 5.2: Axiom of weak associatively states the result of a series of compositions does not

Table 1
Scale types and admissible transformation

Scale name	Admissible transformation g	Interpretation	Meaningful statistics
Nominal	Any one to one g that preserves the grouping	Nominal scales are classifications without any proscribed order. Any transformation that preserves the classification is admissible (e.g. numbering of football players)	Mode
Ordinal	g: strictly increasing monotonic function that preserves order	Ordinal scales rank the objects according to some criterion. Given assignment of one object the assignment of another object is arbitrary as long as the order is preserved (e.g., hardness measurement)	Median
Interval	$g(x) = ax + b$	Interval scales define the distance between measured values (unit) and are thus meaningful but the values themselves are not meaningful since no zero element is defined (e.g. temperature measured as Celsius or Fahrenheit)	Mean
Ratio	$g(x) = ax$	Ratio scales have a meaningful zero point and unit. The ratios between values are therefore meaningful (e.g. distance measured in meters or temperature measured in Kelvin)	Mean
Absolute	$g(x) = x$	Absolute scales have only a single measure (e.g. counting is usually an absolute scale)	All

depend on the order in which they are carried out: $o_1 \circ (o_2 \circ o_3) = (o_1 \circ o_2) \circ o_3$.

Axiom 5.3: Axiom of weak commutatively states the order of concatenation does not matter: $o_1 \circ o_2 = o_2 \circ o_1$.

Axiom 5.4: Axiom of weak monotonicity states the composition preserves the ordering between objects:

$$o_1 \succcurlyeq o_2 \Rightarrow o_1 \circ o_3 \succcurlyeq o_2 \circ o_3.$$

Axiom 5.5: Archimedean Axiom states that if $o_3 \succcurlyeq o_4$ then for any o_1, o_2 there exists a natural number n such that $o_1 \circ no_3 \succcurlyeq o_2 \circ no_4$.

Definition 6 (Absolute scale). The relational system $(O, \succeq, \circ)$ is an absolute scale if and only if there is a numerical relational structure $(\boldsymbol{R}, \geq, \otimes)$ such that the following condition holds: Z is the set of N-representations for E that are onto Z and Z has exactly one element.

The definition for absolute scale indicates there is only one measure for absolute scales and this explains why there is only a single admissible transformation; i.e. identity.

Each scale type has its interpretations, admissible transformations, and meaningful statistical analysis summarized in Table 1.

3. Measurement framework

The measurement framework is based on relational measurement theory as presented in the previous section. The analysis considers the following issues:

1. Empirical system: The measurement framework requires a clear understanding of the empirical system, definition of the objects and qualitative relationships between them. Three questions are

analyzed: (1) what are the objects measured? (2) what is the empirical relation? And (3) based on the system definition is the measure structural or operational? The later question is determined by analyzing whether the system property can be specified without reference to the system's operating environment.
2. Representation condition: An analysis of whether the proposed measure obeys the representation condition (1) is conducted.
3. Scale and axiom type: All measures are analyzed for the weak order axioms since these establish the minimum requirements for a measure. For the interval, ratio, and absolute scales each measure is analyzed according to the axioms for its scale type.
4. Concatenation operator: Analysis of whether the empirical system requires an additive property. If yes, then does the measure have a concatenation operator. Few researchers have explicitly considered additive properties of systems so when needed we define a concatenation operator based on the definition of the system and measure.

3.1. Comparison with other measurement frameworks

The reviews conducted by Sethi and Sethi (1990), Shewchuk and Moodie (1998), and Parker and Wirth (1999) focus on elucidating the empirical system. Each successive work adds to our understanding of the empirical system, the objects of concern, and the empirical relationships. In Sethi and Sethi (1990) there are many measures classified together under the same name implying they are interchangeable for that flexibility property. Shewchuk and Moodie (1998) provide a taxonomy for classifying flexibility measures according to six attributes: level of manufacturing requirements specification, manufacturing system specification, manufacturing environment specification, flexibility dimension, flexibility measurement approach, and time frame. The more detailed and rigorous classification provided by Shewchuk and Moodie (1998) show that many measures purporting to measure the same property are in fact measuring different things. Parker and Wirth (1999) analyze flexibility measures based on the purpose of the measure and what criteria the measure should meet. In the measurement theoretical framework presented here this is formalized in the representational condition. From the measurement theoretical perspective these authors have elucidated the empirical system but have paid less attention to the measurements as mathematical mappings. The measurement theoretical framework presented here extends these earlier works by analyzing the mathematical mappings from the empirical system into a numerical system and the properties of those mappings. The importance of the mappings are at least threefold (1) understanding mathematical properties of mapping, (2) detecting undesirable properties of mapping, and (3) correctly using the resulting numbers in statistical and related analysis. The second difference is the above classifications are limited to flexibility; the measurement theoretical framework is applicable to any structural measure of the system including agility, scalability, and others.

4. Measurement analysis summary

Flexibility measurement has been widely studied (see for example Browne et al., 1984; Gupta and Goyal, 1989; Mandelbaum and Brill, 1989; Sethi and Sethi, 1990; Parker and Wirth, 1999) and has lead to a classification of flexibility types of machine, material handling, operation, process, routing, product, volume, and expansion. In addition to the now standard categorization originally published by Browne et al. (1984) authors have expanded the concept of flexibility into the supply chain (Beamon, 1998, 1999), product development (Thomke and Reinerstein, 1998; Sieger et al., 2000) and other areas of the enterprise. Agility as a property is less formally developed and a consensus of agility factors has not emerged yet. Agility was investigated by the Agility Forum (1994) which proposed four strategic dimensions of agile competition and was expanded by Goldman et al. (1995) to include: (1) enriching the customer, (2) cooperating to compete, (3) organizing to master change and uncertainty, and (4) leverage the impact of people and information. Several authors based their measurement on these general dimensions. Dove (1994) was one of the first to discuss agility measurement. Dove cites four indicators of cost, time, robustness, and scope that can aid in monitoring the capability of a process to respond to unanticipated change. There are no accepted standard definition of agility types so any comparisons between measures is done based on the measure descriptions provided by the authors. The complete analysis of flexibility and agility measures with respect to the measurement framework is summarized in Table 2. In the following subsections we use the measurement framework to provide a more detailed analysis of (1) structural versus operational; (2) problems due to representation condition; (3) scale types and axioms; and (4) additive property and concatenation.

4.1. Structural versus operational measures

The measures are classified into two groups, structural and operational. The measures determined to be of the structural type are: agility time delay, agility distance, expansion flexibility, machine flexibility, material handling flexibility, operation flexibility, process flexibility, routing flexibility, and volume flexibility. These measures all seek to represent an intrinsic property of the system due to the system components and how they are related without reference to the operating environment. For example, material handing flexibility is defined for a system design (represented by nodes and arcs); it does not depend on operational decisions, part types, or other environmental factors. Some of the measures are structural but for a limited system definition. These include routing flexibility (Chatterjee et al., 1987), process flexibility, and machine flexibility (Sethi and Sethi, 1990). For example, the routing flexibility defined by Chatterjee et al. (1987) requires the specification of the set of parts to be produced by the manufacturing system. The set of parts is external to the system (a system input). However, given the set of parts the routing flexibility as defined is a structural property of the system.

Measures identified as operational are: agility index, agility scorecard, delivery flexibility, flexibility index, product flexibility, and routing flexibility (Browne et al., 1984). These measures all relate to operational decisions of the system. For example, product flexibility (Jaikumar, 1986) when defined as the number of parts introduced per year is operational since it depends on many reasons due to the competitive environment, management decisions, marketing strategy, and so forth that determine how many parts are introduced each year. A structural measure of product flexibility would need to represent the underlying organizational structural such as concurrent engineering or more traditional product development organizations and reveal how they relate to product flexibility. The delivery flexibility (Beamon, 1998) is an operational measure; you must know the parts, due dates, and processing time which all change frequently in the system. Likewise, the routing flexibility as defined by Browne et al. (1984) is operational because it involves many operational issues such as availability of repair crews, maintenance schedules, and scheduling.

The audit type approaches to measurement of Metes et al. (1998), Kumar and Motwani (1995), and van Hoek et al. (2001), which rely on subjective assessments of factors, are classified as an operational measure. An examination of the measurement methodologies reveals why they are operational measures. Metes et al. (1998) extend the change proficiency domains introduced by Dove (1994) to agile networking to be used as an agility metric. The methodology involves six steps using a scorecard to assess different agility domains. The scorecard is a matrix that maps standard agility domains against agile networking capability and requires a two-pass approach. In the first pass each box is assigned values from 1 (Worst) to 9 (Superior) but the author recommends to dwell on extremes and try not to use 4, 5 or 6. This permits identification of the areas of excellence and areas of deficiency. On the second pass map more entries but this time you may use values of 4, 5 and 6. Once the matrix is fully

Table 2
Analysis of measures according to measurement framework (empirical system, representation condition, weak order

Measure	Reference	Definition	Empirical system: Entities	Empirical system: Relation	Structural/ Operational	Representation condition: $x > y$ then $M(x) > M(y)$	Representation condition: $M(x) > M(y)$ then $x > y$	Weak order: Transitive	Weak order: Complete
Agility distance metric	Goranson (2000)	Number of each node type raised to the power of its type. (where type is the out-degree of the node).	Enterprise	"Is more complex than"	Structural	Yes	No	—	—
Agility index	Kumar and Motwani (1995) and Martinez (2000)	Y_{ij} are subjective measures of agility factor i during time period j.	Enterprise	Is more agile than	Operational	Yes	Yes	Yes	Yes
Agility scorecard	Metes (1998)	Many individual enterprise attributes measured on a five point scale (subjective).	Enterprise	Is more agile than	Operational	Yes	Yes	Yes	Yes
Agility time delay metric	Goranson (2000)	Number of sub-conversations (loops).	Enterprise	"Is more complex than"	Structural	Yes	No	—	—
Delivery flexibility	Beamon (1999)	Ability to move planned delivery dates forward.	Set of orders	Is more capable to move forward than	Operational	Yes	Yes	Yes	Yes
Expansion flexibility	Parker and Wirth (1999)	Ability to easily add capacity to a system.	Facility	Easier to add capacity than	Structural	Yes	Yes	Yes	Yes
Flexibility index	Thomke and Reinerstein (1998)	Ratio of percent change in modified design or product requirements and the percent change in estimated life-cycle profits.	Design process	Has higher ratio of design change/ estimated profits	Operational	No	Yes	—	—
Machine flexibility	Gerwin (1987)	Extent of variations in key dimensions the raw input material.	Machine	Is wider than	Structural	Yes	Yes	Yes	Yes
Machine flexibility	Sethi and Sethi (1990), Tsubone and Horikawa (1999)	Ratio of the number of operations that can be processed without changing the setup when switching to	Machine	Has higher ratio of operations for one setup per total	Structural	No	No	—	—

		another operation to the total number of operations processed		operations than					
Machine flexibility	Sethi and Sethi (1990)	Ratio of operations a machine can perform/switching cost	Machine	Has higher ratio of operations/switching cost than	Structural (constrained)	Yes	Yes	Yes	Yes
Machine resetting flexibility (FR)	Taymaz (1989)	Time to reset from one operation to another operation	Operations	Is lower time than	Structural	Yes	No (yes with weaker condition)*	Yes	Yes
Machine setup flexibility (FS)	Taymaz (1989)	Cost to set up from one operation to another operation	Operation	Is lower cost than	Structural	Yes	No (yes with weaker condition)*	—	—
Material handling flexibility	Stecke and Browne (1985)	Ordinal ranking of material handling equipment	Machine	More flexible than	Structural	Yes	Yes	Yes	Yes
Material handling flexibility	Chatterjee et al. (1987)	Number of paths supported compared to total number of potential paths	Material handling system	Has higher proportion of paths than	Structural	Yes	No (yes when comparing systems of same size)	Yes	Yes
Operational flexibility	Sethi and Sethi (1990)	The number of different process plans for a part	Part	More operational flexibility than	Structural	Yes	Yes	Yes	Yes
Process flexibility	Proth (1982)	Range of sizes a machine or system can produce	Machine	Larger range than	Structural	Yes	Yes	Yes	Yes
Process flexibility	Browne et al. (1984)	Number of part types to produce without major setups	Machine	Larger number than	Structural (constrained)	Yes	Yes	Yes	Yes
Product flexibility	Jaikumar (1986)	Number of parts introduced per year	Part	More parts introduced per year than	Operational	Yes	Yes	Yes	Yes
Routing flexibility	Browne et al. (1984)	Percent decrease in throughput due to a machine breakdown	Manufacturing system	Lower percent decrease than	Operational	Yes	Yes	Yes	Yes
Routing flexibility	Tsubone and Horikawa (1999)	Ratio of the number of operations performable on an alternative machine to the total number of operations assigned a certain machine	Manufacturing system	Has higher ratio of operations performable on alternative machines	Structural	Yes	Yes	Yes	Yes

Table 2 (*continued*)
Analysis of measures according to measurement framework (empirical system, representation condition, weak order

			Empirical system			Representation condition		Weak order	
Measure	Reference	Definition	Entities	Relation	Structural/ Operational	$x > y$ then $M(x) > M(y)$	$M(x) > M(y)$ then $x > y$	Transitive	Complete
Routing flexibility	Chang et al. (1989)	Average number of machines capable of processing an operation	Set of machines (e.g. FMS)	Can process more than	Structural (constrained)	Yes	Yes	Yes	Yes
Routing flexibility	Chatterjee et al. (1987)	Number of ways to process a part type in the system	Manufacturing system	More ways than	Structural (constrained)	Yes	Yes	Yes	Yes
Routing flexibility	Carter (1986)	Ratio of number of routes to total possible routes.	System	Higher number routes to total number routes ratio than	Structural (constrained)	Yes	Yes	Yes	Yes
Routing flexibility	Gerwin (1982)	Rerouting of a part if a machine used is incapacitated	Manufacturing system	Has greater capability to reroute than	Structural (constrained)	Yes	Yes*	Yes	Yes
Volume flexibility	Parker and Wirth (1999)	Ability to operate efficiently, effectively, and profitability over a range of volumes	Manufacturing system	Has a larger range of profitable volumes than	Structural	Yes	Yes	Yes	Yes

populated work can begin on balancing agile networking capabilities. Kumar and Motwani (1995) claim that agility refers to an enterprise's ability to accelerate the activities on the critical path, and is, therefore, a direct indicator of an enterprise's time-based competitiveness. To determine the effectiveness of a firm to compete on time, they have developed a measure called the *agility index*. The agility index provides the composite value of the strategic agility position of a firm on a percentage scale. The agility index (AI) is implemented with a matrix where each row i represents the agility determinants (information flow discipline, technology, human resource, quality, and flexibility) and each column j represents time on the critical path (product design, prototyping, production, manufacturing, and delivery) of the firm. Weights are assigned to each column and each row. Through an empirical evaluation the firm under analysis assesses its position vis-à-vis its competitors on the various dimensions as a time-based competitor by assigning scores between 1 and 10 for each box Y_{ij}, where each Y_{ij} is an ordinal measure of factor i in time period j. The agility index AI is the weighted sum of these values. The agility index was empirically tested by Martinez (2000) who adapted the audit approach to conduct a focused study of 80 medical instrument device manufacturers. In a similar vain van Hoek et al. (2001) created a scorecard based on factors from Goldman et al. (1995) and use a five point Likert scale to survey managers. These audit approaches do not attempt to model any underlying structural properties of the enterprise. They seek correlation between management practices and performance and are consequently classified as operational measures.

The only attempt found of directly measuring structural agility are the measures of Goranson (2000). Goranson (2000) proposes modeling agile virtual enterprises and their interaction using speech-act theory. Building a graph of a conversation where nodes represent entities and arcs represent speech-acts between those entities he then proposes two measures on the graph structure as agility metrics. The *distance metric* is a function of the number of arcs connected to the node called the out-degree type of the node. The distance metric is the sum of the number of each node type raised to the power of its type. The second metric is called the *time delay metric* and is the sum of the number of loops in the graph. The two metrics are of the underlying business communication and are consequently structural measures.

4.2. Representation condition

Using the framework we can identify some problems in measures, shown in Table 3, because they do not conform to the representation condition (Eq. (1)) of the measurement framework. The flexibility index by Thomke and Reinerstein (1998) can conceivably lead to a value of infinite flexibility when the estimated life-cycle profits are zero. Such a situation could arise when a company is updating a product design to merely stay competitive in the market. Our intuition of the empirical system is that if the expected profits were zero then the preferred situation would be a low cost in implementing the design change. The FI is a partial order that ranks all zero expected profit changes equally and consequently the measure cannot differentiate among these cases. For this reason it violates the representation condition because it does not preserve the empirical relationship for these cases.

The agility measures of Goranson (2000) do not adhere to the representational condition. The author argues the more nodes and loops in the conversation graph indicate a complex and difficult to change business process. Consequently, the higher the measure the less agile the enterprise is. The two measures do not adhere to the representation condition (1) since the relationship in the empirical system, "*system A is more agile than system B*" maps into $A < B$ in the numerical system. Such a relationship seems counterintuitive. The reason for the reverse ordering is Goranson (2000) is directly measuring complexity and then arguing that the more complex a process the more difficult to change it and consequently the less agile the process is. These issues do not necessarily invalidate the measure but it is important for practitioners to be aware of them. In the case of Goranson's metrics the practitioner must realize they are measuring complexity and should be categorized as the dimension "mastering change and uncertainty" in the framework defined by Goldman et al. (1995).

Delivery flexibility (DF) is the ability to move planned delivery dates forward and would aid the accommodation of rush orders or special orders in the supply chain (Beamon, 1998, 1999). The measure is defined as the proportion of excess slack time across all jobs j. Slack time is the difference between the current time period t and the due date period L. If the earliest date on which the delivery can be made is E, then

$$\mathrm{DF} = \frac{\sum_j (L_j - E_j)}{\sum_j (L_j - t)}. \tag{2}$$

DF is zero when the earliest all the jobs can be delivered is on the due date. DF is 1 when the earliest date equals the current date t. The measure

Table 4
Ordinal scale measures

Measure	Reference
Agility distance metric	Goranson (2000)
Agility index	Kumar and Motwani (1995); Martinez (2000)
Agility scorecard	Metes (1998)
Agility time delay metric	Goranson (2000)
Material handling flexibility	Stecke and Browne (1985)

Table 3
Problems identified in analysis

Measure (reference)	Non-conformance
Agility distance metric (Goranson, 2000) Agility time metric (Goranson, 2000)	A lower value is more agile.
Machine resetting flexibility (Taymaz, 1989) Machine setup flexibility (Taymaz, 1989)	A matrix represents the cost from one operation to another. All elements of one matrix must be greater than the corresponding elements of the other matrix for $M(x) > M(y)$. The author remarks that the condition is very strong and a weaker condition is possible.
Machine flexibility (Sethi and Sethi, 1990; Tsubone and Horikawa, 1999)	Suppose M1 can process without setup the parts {ABC} and {DE} and M2 can process without setup {ABCD} and {E}. MF1 = 3/5, 2/5 and MF2 = 4/5, 1/5. The measure does not tell you how to compare sets of values when MF1 < MF2 for the first set and MF1 > MF2 for second set.
Material handling flexibility (Chatterjee et al., 1987)	When comparing systems with same number of nodes then representation condition satisfied. When comparing systems with different number of nodes it is not clear in the empirical system whether system A is more flexible than system B.
Flexibility index (Thomke and Reinerstein, 1998)	Cannot differentiate between two alternatives with zero profits but different cost structures.
Product flexibility (Jaikumar, 1986)	The measure is of what was done not what the system is capable of.
Delivery Flexibility (Beamon 1998, 1999)	Suppose the current time period is four and there are five jobs with due dates 12, 14, 16, 18, and 20, respectively. The earliest they can be made is 11, 13, 15, 17, and 19, respectively. This is scenario A. In scenario B, the due dates are 11, 13, 15, 17, and 19 but the earliest they can be made is 10, 12, 14, 16, and 18, respectively. Then DF(A) = 0.0.083 and DF(B) = 0.091. Yet the slack is one day for each job in both scenarios and thus they have the same ability to move planned due dates forward. Many production managers would be indifferent between the two scenarios, yet the measure suggests that B is preferred to A.

Table 5
Ratio scale measures

Measure	Reference	Associative	Commutative	Montonic	Archimedean
Machine flexibility	Gerwin (1987) SS	Yes	Yes	Yes	Yes
Process flexibility	Proth (1985)	Yes	Yes	Yes	No (ranges can overlap)
Volume flexibility	Parker and Wirth (1999)	Yes	Yes	Yes	Yes

Table 6
Absolute scale measures

Machine resetting flexibility (FR)	Taymaz (1989)
Machine setup flexibility (FS)	Taymaz (1989)
Material handling	Chatterjee et al. (1987)
Operational flexibility	Sethi and Sethi (1990)
Process flexibility	Browne et al. (1984)
Product flexibility	Jaikumar (1986)
Routing flexibility	Chatterjee et al. (1987)
Routing flexibility	Carter (1986)
Routing flexibility	Browne et al. (1984)
Routing flexibility	Chang et al. (1989)

is a ratio of possible range of slack time periods over the total periods. The measure conforms with the representation condition whenever the denominator or total time periods between current date and all due dates is the same for the two scenarios being compared. When the denominator is different then the delivery flexibility measure may provide a counter-intuitive ordering (see Table 3).

4.3. Scale types and axioms

The measures classified according to scales are shown in Tables 4–6. Knowing the scale type is important for interpreting the measure correctly, what statistical operators are valid, and for correctly interpreting the meaningfulness of statements. In Table 1 we showed the correct interpretation and example statistics. For example, the Y_{ij}'s of the Agility Index are an ordinal scale, therefore, statements such as manufacturing firm A is twice as agile as firm B are meaningless because ordinal scales do not define a unit between the measures. So when Martinez (2000) analyzed different company's agility index the scores can only be used for ranking since the intervals between numbers are meaningless for ordinal measures. Second, the scales dictate the meaningful statistic operators, so for example, the median of several firms' AI has significance but the mean is meaningless because the mean is not a proper statistical function for the ordinal scale. The scales also let us analyze different measures for proper usage. Goranson (2000) says to add the distance and time agility metrics together to provide a number where the higher the number the less agile the enterprise. The addition of two measures is inconsistent with the measurement framework since the two measures are ordinal measures and have dissimilar units. Finally, scale types are indicators of the level of knowledge of the underlying empirical system. Scales are order from ordinal, interval, ratio, to absolute. The more sophisticated scales such as ratio and absolute provide more information and allow more statistical operators. For example, ratio scales have defined units between successive measures which provides information on the difference between measures that ordinal scales cannot capture.

4.4. Additive property and concatenation axiom

For some structural properties the additive property is very important and the measurement framework indicates that researchers have been amiss in not defining concatenation operators (such as by Definitions 4 and 5) for the objects being measured. For example, the strategy inherent in agile virtual enterprises dictates the opportunistic short-lived mergers between organizations for exploiting fleeting market needs. Clearly, a measure for an agile virtual enterprise would need to evaluate the impact of the merger and thus have

Table 7
Additive property needed

Agility distance metric
Agility time delay metric
Expansion flexibility
Routing flexibility
Volume flexibility
Agility index
Agility scorecard
Material handling

defined a concatenation operator. Goranson's (2000) metrics consider this issue as an "AS-IS" and "TO-BE" graph but do not explicitly define how new nodes or arcs can be concatenated onto the graph structure they define. In Table 7 we list measures where the empirical system needs an additive property. None of the measures cited provide a defined method for adding two objects so we show an approach using volume flexibility as an example.

The volume flexibility measure (Parker and Wirth, 1999) needs to consider concatenation so that companies can evaluate strategic decisions involving acquisition of greater capacity (i.e. volume). The authors do not directly address the merging of two facilities so we show how to define an appropriate concatenation. Volume flexibility (VF) of a manufacturing system is its ability to be operated profitably at different overall output levels (Parker and Wirth, 1999). The measure is defined for multiple products as

$$\mathrm{VF} = \frac{1-F}{C_{\max}}\left(\prod_i \frac{a_i}{b_i}\right)^{1/n} \tag{3}$$

where F is the fixed costs to operate the facility, $C_{\max}$ is the maximum capacity of the facility, a_i is the number of capacity units required to product part i, and b_i is the contribution to profit margin for product i. b_i is the difference between price and cost of product i. VF ranges between 0 and 1 and adheres to the representation condition. Concatenation of two facilities is defined as the joining of the facilities such that the maximum capacities are additive, the fixed costs are additive, a_i remains unchanged, and b_i remains unchanged. Given this concatenation definition the axioms for a ratio structure are obeyed.

5. Conclusions

A system exhibits both structural properties and operational properties; and system design, management, and improvement must analyze both sets of properties. This article defined and classified the extant measures according to whether they are structural or operational. A measurement framework was developed based on relational measurement theory. Using the measurement framework both flexibility and agility measures were analyzed. The measurement framework also can be used going forward to aid system designers to formally define desirable properties, their meaning, and how to measure them. The measurement framework and analysis makes three main contributions.

The first contribution is the evaluation with the measurement framework reveals some discernable trends in the development of system measures. First, it is seen that flexibility definitions and measures are more sophisticated and developed than agility measures. Many of the flexibility measures are of absolute scale, the most sophisticated scale which allows a wide range of statistical operations. All of the agility measures are ordinal scale, which is the lowest level scale to be considered measurement. The reason for the difference can be attributed to the longer history of flexibility research compared to agility, which has resulted in a better understood and defined empirical system for flexibility. Thus, for flexibility more research should transition from considering the definitions of flexibility to the mappings and empirical research of correlating the flexibility measures to performance measures. Concerning agility, researchers are still at the stage of defining factors or determinants of agility. Most agility measurements are more of an audit of trying to find factors that may correlate to a concept of agility. Greater work is needed in defining agility measures so that progress in measurement may be made.[1] The measurement framework can be utilized to establish this formal foundation for structural agility measures and promises an evolution to more sophisticated measurements and the benefits inherent therein.

The second main contribution is this article is the first to formally analyze the mathematical mappings from the empirical system to the numerical system. Most research in flexibility or agility measurement still concentrate on the elucidation of the empirical system by definition of the objects and relationships. The measurement framework, and specifically the relational condition defines a requirement for how to represent those empirical objects and relationships in a formal numerical system. In some cases the lack of a rigorous and formal theory for developing measures has lead to poor properties of the measures; for example, the flexibility index can possibly go to infinity in some cases and more importantly it cannot differentiate between two different scenarios if both have zero expected profit from a design change. Utilizing the measurement framework and adhering to the representational condition can alleviate these problems. The relationship condition also suggests that future research instead of trying to find a single measure to capture many concepts; they start with a single measure for each empirical relationship. Thus, instead of trying to define a single agility index the individual subfactors should be more clearly defined and measured.

The third main contribution of the measurement framework relates to measurement concepts that have not been addressed by the literature. The additive concept is important, especially with many systems experiencing mergers, acquisitions, or divestures of significant holdings. Measures such as volume flexibility, agility, and others mentioned need to be able to evaluate the impact of changes to the system. In order for management to evaluate such changes to the system, the measures must have the properties defined for the concatenation operator by the measurement framework. No measures analyzed explicitly consider the issue of concatenation. The scale of the measure is also often overlooked, knowing the scale is important to determine the meaningful statistics that can be applied and the measure's correct interpretation.

[1] In measurement of temperature there is a good example of the developmental phases of measurement. Early (prehistoric) notions of temperature were probably ordinal (i.e. A is hotter than B), then development of interval scales such as Fahrenheit and Celsius that define a unit (interval) between successive items. The more sophisticated ratio scale was obtained by Kelvin, which identified an absolute zero element. As our understanding of the empirical system temperature grew the sophistication of our measurement increased.

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