KNOWLEDGE-BASED MEASUREMENT OF ENTERPRISE AGILITY

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1. INTRODUCTION

One essential requirement for business survival is the continuous ability to meet customer needs and demands. Market needs cause unceasing changes in product(s) life cycle, shape, quality, and price. Agility is an enterprise-wide response to an increasingly competitive and changing business environment, based on four cardinal principles: enrich the customer; master change and uncertainty; leverage human resources; and cooperate to compete [1], [2].

Agility is more formally defined as the ability of an enterprise to operate profitably in a rapidly changing and continuously fragmenting global market environment by producing high-quality, high-performance, customer-configured goods and services. It is the outcome of technological achievement, advanced organizational and managerial structure and practice, but also a product of human abilities, skills, and motivations [2].

The application of agile manufacturing methods started in the late 1980s as a response to competition from Japan and the other Pacific Rim area countries. Some of these methods include *just-in-time manufacturing*, *flexible manufacturing systems*, *computer* and *communication networks*. Several programs and initiatives started to help U.S. companies change their organization and production processes [2]. Such programs include the Department of Energy's (DoE) *Demand Activated Manufacturing Architecture* [11] (textile/apparel industries), Technologies Enabling Agile Manufacturing (TEAM) [12], etc. In addition, several Agile Manufacturing Research Institutes (AMRIs) have already been established, like the Aerospace Agile Manufacturing Research Center, the

Machine Tool Agile Manufacturing Research Institute (MT-AMRI), and the Rensselaer Electronics Agile Manufacturing Research Institute (EAMRI). These institutes and their activities have been described in [10].

Agility, like many other general concepts, is ill defined and thus has a different meaning for different people, even within the same organization. Very often agility is confused with flexibility. In manufacturing terms, flexibility refers to product(s) range using certain (production) strategies, while agility refers to quick movement (change) of the whole enterprise in a certain direction. Flexibility normally refers to the capabilities of a factory floor to rapidly change from one task or from one production route to another, including the ability to change from one situation to another, with each situation not always defined ahead of time. Agility refers to the strategic ability of an enterprise to adapt and accommodate quickly unplanned and sudden changes in market opportunities and pressures, thus, in this sense it is wider than flexibility.

The problems in measuring both flexibility and agility are more or less the same. Similar to the case of measuring manufacturing flexibility [17], there does not exist a direct, adaptive and holistic treatment of agility components. In [3], the overall problem of agility measurement is limited to three simple, yet fundamental questions: what to measure, how to measure it, how to evaluate the results. Furthermore, there is no *"synthesis method"* to combine measurements and determine agility. Indeed, literature review reveals overlaps in the dimensions of agility as well as lack of a universal metric [4]. There does not appear to be a measure that identifies certain parameters/indicators of the agility level, albeit some efforts in that direction. Some guidelines towards agility measurement together with the difficulties of such a task are given in [2], along with a comprehensive questionnaire for the monitoring of various agility factors. These questions are useful because they can be part of the knowledge acquisition procedure of any knowledge-based agility measure. However, it should be emphasized that the agile manufacturing literature is rife with generalities especially when comes to agility metrics.

An agility measurement methodology based on the acquired knowledge, is described in this chapter. Knowledge is represented via linguistic IF-THEN rules, which has a number of clear advantages over other representation techniques. First and foremost advantage is the rule simplicity. The *know-how* knowledge for measuring agility can be, in most cases, easily modeled by the IF-THEN rules. Further, it is easy to make logical inferences, in which various forms of uncertainty and fuzziness are present.

This chapter is the based on the research reported by Tsourveloudis and Valavanis in [15]. The proposed framework aims at providing the fundamentals of an adaptive knowledge-based methodology for the measurement of agility. The definition and derivation of a combined agility measure is based on a well-defined group of individually defined (and then grouped) quantitative metrics. By utilizing these metrics, decision-makers have the opportunity to examine and compare different systems at different agility levels.

The rest of the chapter is organized as follows. In Section 2, some general steps for achieving and managing agility, are provided. Guidelines for the construction of any agility measure along with the characteristics and the mathematical formulation of the proposed methodology are presented in Section 3. In Section 4, we define four distinct agility infrastructures used for the measurement. Specific measuring variables are defined and explained. Section 5 gives a brief arithmetic example of the methodology. The chapter concludes with discussion and a remarks section.

2. MANAGING AN ADAPTIVE INFRASTRUCTURE

Global market needs cause unceasing changes in the life cycle, shape, quality, and price of products. Manufacturing competitiveness has moved from the *"era of mass production"* to the *"era of agility"*. It is common belief, today, that the business environment is changing faster than firm's ability to enable change. Yesterday's production infrastructure was built for continuous production, stability and manageability. Even the reengineering initiatives of a decade ago were more about redesigning new processes rather than making those processes easy to change over time. The agility era requires a production infrastructure that has the capacity to adapt and deliver measurable improvements in manufacturing processes. An adaptive production infrastructure responds rapidly to new business conditions and opportunities, takes advantage of new technologies, accommodates unanticipated changes and demonstrates the value of agility through a measurements-driven approach.

An adaptive production/manufacturing infrastructure can expand or shrink in alignment with business needs. It is useful to see a manufacturing system from a design viewpoint. All manufacturing infrastructures can break down in conceptual components, the integration of which makes the manufacturing system. These components are: *Materials, Processes, Equipments/Tools, Facilities, Support/Logistics and People.* In many cases, the "system" fails because the above-mentioned components are viewed separately or fail to understand the dynamic nature of information going over the production infrastructure. A three steps approach for minimizing the "agility gap" in manufacturing systems management may be the following:

Step 1: Design and plan agility improvements. It is essential to identify business challenges and processes for which agility is a basic factor. Key considerations include the company's business strategy, relevant industry and technological trends, competitive pressures and the overall economic environment. Important questions to answer: What does it mean for a particular manufacturing system to be agile? How agile is the system now? What will it take to achieve the desired results? What is the cost for these changes?

Step 2: Built an adaptive infrastructure according to the four fundamental agility design principles: 1) enrich the customer; 2) master change and uncertainty; 3) leverage human resources; and 4) cooperate to compete. The infrastructure must be built to utilize agility metrics and diagnostics. Adaptive infrastructure solutions need to deliver against some combination of the three key agility metrics: time, range and ease. General conditions for achieving agile manufacturing are the following [17]:

- High degree of integration in company not based only on the information technology, but also on the human mutual interconnection,
- Establishing of work teams based on natural and logical associations,
- It is necessary to raise the responsibility level of all employees,
- Continuous learning, training, testing and introducing of novelties,
- It is necessary to introduce a virtual company,
- High trained and versatile experts organized in teams and
- Introducing of knowledge, changes and risk management.

These requirements must be adapted to the specific needs of a company with respect to the type of production.

Step 3: Measure agility results. Regardless of the structure of the agility measure, it is important that any practical agility metric should [18], [14]:

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

3. AGILITY MODELING AND MEASUREMENT FUNDAMENTALS

Measuring agility is not a trivial task. Agility metrics are difficult to be defined, mainly due to the multidimensionality and vagueness of the concept of agility [18]. However, in order someone to understand and employ the agile manufacturing principles has to be able to measure agility. In [3], the overall problem of measurement is limited to three simple, yet fundamental questions: what to measure, how to measure it, how to evaluate the results. More recent approaches utilize knowledge-based techniques, such as fuzzy logic, for the assessment of manufacturing agility ([18], [14]). In these works, the overall agility is measured by the synthesis of individual infrastructures identified in the enterprise.

Regardless of the structure of each measure, it is important to establish basic principles, which should be satisfied by any such agility measure. It is postulated that any practical agility metric should provide a situation specific measurement by taking into account the particular characteristics of the system/enterprise under study, and allow for comparisons among different installations. Further, it should incorporate all the relevant to agility accumulated human knowledge/expertise by focusing on specific observable measuring parameters that may be defined. In view of the above statements, the proposed agility measurement scheme is [15]:

1. **Direct:** it focuses on the observable operational characteristics that affect agility (direct measurement), such as product variety, versatility, change in quality, networking

etc., and not on the effects of agility (indirect measurement) such as, increased assets or profits, short delivery times, customer satisfaction, etc. The proposed method provides context-specific measurements but without changing its structural characteristics every time. The measure will adapt to different manufacturing systems/enterprises and allow agility comparisons among them.

2. **Knowledge-based:** it is based on the expert knowledge accumulated from the operation of the system under examination, or on similar systems. A good metric should be capable of handling both numerical and linguistic data, resulting in precise/crisp (e.g. agility = 0.85) and/or qualitative (e.g. high agility) measurements.
3. **Holistic:** it combines all known dimensions of agility. Agility is a multidimensional notion, observable in almost all hierarchical levels of an enterprise. For quantification purposes, it is categorized into several distinct (enterprise) *infrastructures*.

3.1. Dimensions of agility

Manufacturing systems engineering lacks analytic and closed-form mathematical solutions albeit in the simplest possible cases. Since manufacturing systems are operated and managed by people, it is necessary to record and utilize human knowledge and perceptions about agility and its factors (parameter quantification and measurement). Algebraic formulae fail in putting together the various dimensions of agility coupled with the human perception of agility. To overcome such problems, the key idea is to model human inference, or equivalently, to imitate the mental procedure through which experts (managers, engineers, operators, researchers) arrive at a value of agility by reasoning from various sources of evidence. To quantify agility, managers and operators, frequently use verbal or linguistic values, such as low, average, about high and so on. Thus, a valid and suitable candidate solution to the problem of measuring enterprise agility should be based on fuzzy logic.

The essential concept in agile manufacturing is the integration of organization, people, and technology into a coordinated interdependent system [2], which responds rapidly to changes. The proposed measuring approach involves all the founding concepts of agility expressed, for the sake of analysis, in the following divisions/infrastructures ([14], [15], [18]):

- **Production Infrastructure:** Deals with plant, processes, equipment, layout, material handling, etc. It can be measured in terms of time and cost needed to face unanticipated changes in the production system.
- **Market Infrastructure:** Deals with the external enterprise environment, including customer service and marketing feedback. It may be measured by the ability of the enterprise to identify opportunities, deliver, upgrade products/enrich services, and expand.
- **People Infrastructure:** Deals with the people within the organization. The level of training and motivation of personnel may measure it.
- **Information Infrastructure:** Deals with the information flow within and outside the enterprise. It may be measured by the ability to capture, manage, and share structured information to support the area of interest.

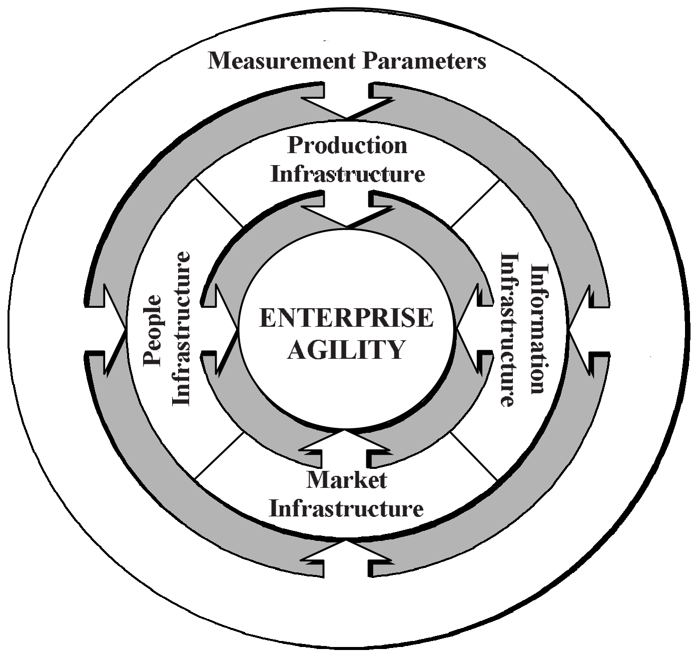

Figure 1. The architecture of the proposed assessment of agility.

The key idea of this approach is to combine all infrastructures and their corresponding operational parameters as shown in Figure 1, to determine the overall agility. The value of agility is given by an approximate reasoning method taking into account the knowledge that is included in simple IF-THEN rules. This is implemented via multi-antecedent fuzzy IF-THEN rules, which are conditional statements that relate the observations concerning the allocated divisions (IF-part) with the value of agility (THEN-part).

Generally speaking, IF-THEN rules are statements of the form LHS → RHS, where LHS (Left Hand Side) determines the conditions or situations that must be satisfied and RHS (Right Hand Side) is the action(s) that must be taken once the rule is applied (or activated). The terms *premise* or *antecedent* and *conclusion* or *consequent* are frequently used for LHS and RHS, respectively. Each side of a rule may be written in the form of a conjunction:

$$A1, A2, A3, \ldots, An \rightarrow B1, B2, B3, \ldots, Bm,$$

which means that whenever A1, A2, A3, . . . , An hold, actions B1, B2, B3, . . . , Bm must be taken. Many times the above rule is written in a natural language manner as follows:

IF A1, A2, A3, . . . , An THEN B1, B2, B3, . . . , Bm.

An example of such a rule is:

IF the agility of *Production* Infrastructure is *Low*
AND the agility of *Market* Infrastructure is *Average*
AND the agility of *People* Infrastructure is *Average*
AND the agility of *Information* Infrastructure is *Average*
THEN the overall *Enterprise* agility is *About Low*

where *Production*, *Market*, *People*, *Information* infrastructures and *Enterprise agility* are the linguistic variables of the above rule, i.e., variables whose values are linguistic terms such as, *Low*, *Average*, *About Low*, rather than numbers. These linguistic ratings are represented with fuzzy sets having certain mathematical meaning represented by appropriate membership functions. Since the impact of all individual infrastructures on the overall manufacturing agility is hard to be analytically computed, fuzzy rules are derived to represent the accumulated human expertise. In other words, the knowledge concerning agility, which is imprecise or even partially inconsistent, is used to draw conclusions about the value of agility by means of simple calculus.

In order to explain the structure of fuzzy rules and the fuzzy formalism to be used towards measurement, consider that A_i, $i = 1, \ldots, N$, is the set of agility divisions (here $i = 4$), and LA_i the linguistic value of each division. Then, the expert rule can be formulated as follows

$$\text{IF } A_1 \text{ is } LA_1 \text{ AND} \ldots \text{AND } A_N \text{ is } LA_N \text{ THEN } G \text{ is } LG \qquad (1)$$

or, in a compact representation, (LA_1 AND LA_2 AND . . . AND $LA_N \rightarrow LG$), where LG represents the set of linguistic values for enterprise agility G. All linguistic values LA_i and LG are fuzzy sets, with certain membership functions. 'AND' represents the fuzzy conjunction and has various mathematical interpretations within the fuzzy logic literature. Usually it is represented by the intersection of fuzzy sets, which corresponds to a whole class of triangular or T-norms [13]. The selection of the 'AND' connective in the agility rules should be based on empirical testing within a particular installation, as agility means different things to different people.

The parameters at the various agility infrastructures are fuzzy sets with certain membership functions. In fuzzy modeling, most of times the membership functions are empirically chosen. In practice if one knows the extreme values of membership (0: full non-membership, 1: full membership) for a given concept, then one may interpolate between those numbers. In the proposed measurement model the acquired (initial) knowledge is represented with a number of IF-THEN rules. In order to provide a direct measurement of the overall agility one needs to know the agility value of each of the infrastructures. Thus, one has to identify certain parameters that indicate agility for each infrastructure. Before doing so, the agility measurement problem is first formulated via fuzzy logic modeling followed by the definitions of specific measuring parameters for each infrastructure in Section 3.

4. MODELING OF AGILITY INFRASTRUCTURES

4.1. Production infrastructure

Agility at the production infrastructure level allows for quick reactions to unexpected events such as machine breakdowns, and minimizes the effect of interruptions of the production process. It refers to the capability of producing a part in different ways by changing the sequence of operations from the one originally scheduled. In order to achieve agility in the production infrastructure (from now on, *production agility*), a combination of certain desirable characteristics is needed, for example, a combination of multi-purpose machines and fixtures, redundant equipment, material handling devices and process variety. The parameters defined for the measurement of production agility (A_{Prod}), are [15]:

1. *Changeover effort* (S) in time and cost that is required for preparations in order to produce a new product mix. It expresses the ability of a system to absorb demand variations. It includes the *setup time* and cost required for various preparations at the production floor such as tool or part positioning and release, software changes etc. Setup time represents the ability of a machine/workstation to absorb efficiently changes in the production process and it influences production agility heavily when the batch sizes or the products cycle are small. Changeover effort is also associated with the *transfer speed* of the material handling system.
2. *Versatility* (V), which is defined as the variety of operations the production system is capable of performing.
3. *Range of adjustments* or *adjustability* (R) of a system, which is related to the maximum and minimum dimensions of the parts that the production system can handle.
4. *Substitutability* (S_B), which is the ability of a production system to reroute and reschedule jobs effectively under failure conditions. The substitutability index may also be used to characterize some built-in capabilities of the system, for example, real-time scheduling or available transportation links.
5. *Operation Commonality* (C_O), which expresses the number of common operations that a group of machines can perform in order to produce a set of parts.
6. *Variety of loads* (P), which a material handling system carries such as work pieces, tools, jigs, fixtures etc. It is restricted by the volume, dimension, and weight requirements of the load.
7. *Part variety* (V_P), which is associated with the number of new products the manufacturing system is capable of producing in a time period without major investments in machinery. It takes into account all variations of the physical and technical characteristics of the products.
8. *Part commonality* (C_P), which refers to the number of common parts used in the assembly of a final product. It measures the ability of introducing new products fast and economically and also indicates the differences between two parts.

Specifically, let T_i, $i = 1, \ldots, 8$, denote the set of parameters of concern, such that LT_i, are the linguistic values corresponding to each T_i. The rule, which represents the expert knowledge on how all the previously defined parameters affect the production agility A_{Prod}, is:

$$\text{IF } T_1 \text{ is } LT_1 \text{ AND} \ldots \text{AND } T_8 \text{ is } LT_8 \text{ THEN } A_{Prod} \text{ is } LA_{Prod} \tag{2}$$

where LA_{Prod} is the linguistic value of production agility, 'AND' denotes fuzzy conjunction, and $\rightarrow$ is the fuzzy implication.

4.2. Market infrastructure

At the level of market infrastructure, agility is characterized by the ability to identify market opportunities, to develop short-lifetime, by customizable products and services and by the ability to deliver them in varying volumes faster and at a lower price. It is associated with the ability of a firm to change focus by expanding or reducing its activities. The parameters identified for the market infrastructure agility (A_{Market}), are:

1. *Reconfigurability* (P_S) of the product mix. It is defined as the set of part types that can be produced simultaneously or without major setup delays resulting from reconfigurations of large scale.
2. *Modularity index* (M_D), which represents the ease of adding new customized components without significant effort. The significance of product modularity for the agile company is discussed in [5].
3. *Expansion ability* (C_E), which is the time and cost needed to increase/decrease the capacity without affecting the quality, to a given level.
4. *The range of volumes* (R_V) at which the firm is run profitably. It can be regarded as the response to demand variations and implies that the firm is productive even at low utilization. It is also associated with the hiring of temporary personnel to meet changes in market demand.

The generic measuring rule for the agility of this infrastructure, is as follows:

$$\text{IF } T_1 \text{ is } LT_1 \text{ AND} \ldots \text{AND } T_4 \text{ is } LT_4 \text{ THEN } A_{Market} \text{ is } LA_{Market} \tag{3}$$

where the notation in (3) follows that of (2).

4.3. People infrastructure

The profitability of an agile company is determined by the knowledge and the skills of its personnel and the information they have or have access to. Work force empowerment, self-organizing and self-managing cross-functional teams, performance and skill-based compensation, flatter managerial hierarchies, and distributed decision-making authority are all parameters affecting agility. By taking advantage of an agile

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workforce, a firm is able to respond quickly to unexpected workloads that may arise. The variables defined as agility level indicators of this infrastructure (A_{People}), are:

1. *Training level* (W). Personnel training contributes significantly towards agility and it can be achieved through education and cross-training programs.
2. *Job rotation* (J). It is related to training and expresses the frequency with which the workers are transferred to new work positions under normal conditions. The generic fuzzy rule can be written as follows (the notation is similar to (2) and (3)):

$$\text{IF } W \text{ is } LW \text{ AND } J \text{ is } LT \text{ THEN } A_{People} \text{ is } LA_{People} \tag{4}$$

4.4. Information infrastructure

The information infrastructure plays a critical role in the development of the enterprise agile capabilities, especially in the context of global and distributed organizations. The concept of *multi-path agility* [7] is used to improve productivity and response time. It is achieved by improvements in information infrastructure by shortening the response of individual entities on a single path and selecting alternative routes. The variables indicating the information infrastructure agility (A_{Info}) are:

1. *Interoperability* (I), which is a measure of the level of standardization and provides an indication of the information infrastructure agility. In a distributed, virtual organization, the exchange and storage of information is necessary for the proper functioning of the enterprise.
2. *Networking* (N), which includes the communication capabilities of an enterprise are defined through ability to exchange information. This exchange takes place at the management level, production level, etc. How well is an enterprise "connected" and capable to provide and utilize information depends heavily on the networking infrastructure, both density of connections and their functionality (bandwidth, reliability, etc.).

The generic fuzzy rule for this infrastructure can be written as follows:

$$\text{IF } I \text{ is } LI \text{ AND } N \text{ is } LN \text{ THEN } A_{Info} \text{ is } LA_{Info} \tag{5}$$

The notation is similar to (2), (3), (4).

4.5. Discussion

Au: Table 1, ok?

Table 1 lists all proposed parameters for the agility infrastructures modeling and evaluation. The values of these parameters, which can be derived from simulation and/or real-life data, are represented by certain membership functions. Most of times the membership functions are empirically chosen in fuzzy modeling. Mathematically speaking, measurement of membership means assigning numbers to objects (points, concepts,

Table 1 Proposed measurement parameters

Infrastructure	Parameter	Symbol
Production	Changeover effort	S
	Versatility	V
	Range of adjustments or adjustability	R
	Substitutability	S_B
	Operation Commonality	C_O
	Variety of loads	P
	Part variety	V_P
	Part commonality	C_P
Market	Reconfigurability	P_S
	Modularity index	M_D
	Expansion ability	C_E
	Range of volumes	R_V
People	Training level	W
	Job rotation	J
Information	Interoperability	I
	Networking	N

etc.), such that certain relations between numbers reflect analogous relations between objects. For a given context, if we show that there is a mapping $f : E \rightarrow N$ from an empirical relation structure E into a numerical relation structure N, then a scale $\ll E, N, f \gg$ exists [13].

Although, the agility infrastructures and parameters shown in Table I are not independent they are combined via IF-THEN rules, which is the knowledge representation tool within the discussed measuring approach. Given a specific enterprise, and given certain performance criteria, one may experiment with the relative importance of the rules to arrive at what may be considered "acceptable agility measurement". Within the proposed framework, there may be more than one ways to reach such acceptable agility measurements that reflect different relative weights of the agility infrastructures.

There is no proof that the selection of a rule or a membership function is optimal. But after a certain period of measurements for a given enterprise, one may check and evaluate the contribution of each rule (and membership function) in the agility assessment. Rules with no contribution can be deleted. Furthermore, the conjunction operator "AND" used in IF-THEN rules can be represented by a whole class of intersection based connectives. The most frequently used "AND" is the min ($\wedge$) operator. A suitable operator maybe the so-called "compensatory—AND" or "γ-operator" [13], which is an example of averaging operator giving values that range from the intersection to the union of the combined sets, as follows: A AND $B = \gamma(A \cup B) + (1 - \gamma)(A \cap B)$. Specific values of γ could represent experts opinions for a given context. Consider for example the case of "people infrastructure". The fuzzy rules used in the measurement contain two variables, namely, training level W and job rotation J, as follows: IF W is LW AND J is LJ THEN I_{people} is LI. The value of the conjunction (LW AND LJ) controls the level of LI. A pessimistic value

Table 2 Data for the agility infrastructures

	Agility Infrastructures		
Production	Market	People	Information
$<S$ is *Low*$>$ $<V$ is *High*$>$ $<R = 0.8>$ $<S_B = 0.7>$ $<V_P$ is *Average*$>$	$<P_S$ is *Low*$>$ $<M_D = 0.5>$ $<C_E$ is *Low*$>$ $<R_V$ is *Low*$>$	$<W$ is *Average*$>$ $<J$ is *Low*$>$	$<I$ is *Low*$>$ $<N$ is *Low*$>$

($\gamma = 0$) restricts the value of LW AND LJ to the minimum membership, while the optimistic one ($\gamma = 1$) outputs the union of the individual membership functions.

5. AN EXAMPLE

An example of how the measurement methodology works is given in this section. It is important to keep in mind that one can select measuring parameters according to the problem at hand.

Au: Table 2, ok?

Assume that at a given time the agility parameters of an enterprise take the values presented in Table 2. For the parameters that do not appear in Table 2 data are not available.

All variables take values in [0, 1]. The membership functions of the linguistic values are assumed to be sets of ordered pairs (: $(x, \mu(x))$, where x is the value and $\mu(x)$ is the membership grade of x) in the same interval as follows:

Low $= L = \{(0, 1), (0.1, 1), (0.3, 0)\}$,
Almost Low $= AL = \{(0.15, 0), (0.3, 1), (0.45, 0)\}$,
Average $= A = \{(0.3, 0), (0.5, 1), (0.7, 0)\}$,
Almost High $= AH = \{(0.55, 0), (0.7, 1), (0.85, 0)\}$,
High $= H = \{(0.7, 0), (0.9, 1), (1, 1)\}$.

The rules are of the Mamdani type [13] and the connective AND $= \wedge =$ min. For the production infrastructure, A_{Prod}, the activated rules, i.e. rules whose antecedents match the observations and therefore describe better their meaning, are:

IF $<S$ is $L>$ AND $<V$ is $H>$ AND $<R$ is $H>$ AND $<S_B$ is $AH>$ AND $<V_P$ is $A>$ THEN $<A_{Prod}$ is $AH>$,
IF $<S$ is $L>$ AND $<V$ is $H>$ AND $<R$ is $AH>$ AND $<S_B$ is $AH>$ AND $<V_P$ is $A>$ THEN $<A_{Prod}$ is $AH>$.

By applying the individual-rule based inference [9] we compute the discrete membership function of the production infrastructure [15]:

$$LA_{Prod} = \{(0.55, 0), (0.6, 0.5), (0.8, 0.5), (0.85, 0)\}.$$

In practice, a number in [0, 1] may be more preferable than a membership function, in order to represent agility. The procedure that converts a membership function

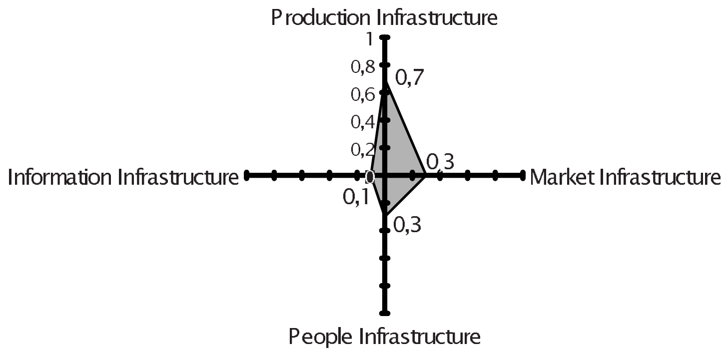

Figure 2. Agility infrastructures plot.

into a single point-wise value, is called *defuzzification*. One can choose among various defuzzification methods reported in the literature. Here, by applying the so-called *Center-of-Area* defuzzification method we derive the crisp value of production infrastructure agility, as follows:

$$defLA_{Prod} = \frac{\sum_{i=1}^{4} x_i \mu_{LA_{Prod}}(x_i)}{\sum_{i=1}^{5} \mu_{LA_{Prod}}(x_i)} = \frac{0 \cdot 0.55 + 0.6 \cdot 0.5 + 0.8 \cdot 0.5 + 0.85 \cdot 0}{0.5 + 0.5} = 0.7.$$

Similarly, the membership functions of market, A_{Market}, people, A_{People} and information, A_{Info}, infrastructures are: $LA_{Market} = \{(0.15, 0), (0.3, 1), (0.45, 0)\}$, $LA_{People} = \{(0.15, 0), (0.3, 1), (0.45, 0)\}$, $LA_{Info} = \{(0, 1), (0.1, 1), (0.3, 0)\}$. The defuzzified/crisp values are $defLA_{Market} = 0.3$, $defLA_{People} = 0.3$ and $defLA_{Info} = 0.1$, as can be seen in Figure 2.

The knowledge concerning the overall agility variations is represented by fuzzy rules as in (1). The rule which is closer to the observations, i.e. computed membership functions of the infrastructures, is:

IF <A_{Prod} is AH> AND <A_{Market} is AL> AND <A_{People} is AL> AND <A_{Info} is L> THEN <G is AL>.

Applying the individual-rule based inference between the above rule and the observed membership functions, we computed the overall agility in a membership function form; that is $LG = \{(0.15, 0), (0.25, 0.5), (0.35, 0.5), (0.45, 0)\}$. The overall agility (in all four infrastructures) is shown with the grey area in Figure 2. The crisp value of agility, according to the *Center-of-Area* defuzzification method is $defLG = 0.3$.

As mentioned in the previous paragraph, most of times the membership functions are empirically chosen in fuzzy modelling. Further, there is no proof that the selection of the shape of a membership function is optimal. In order to examine the effect the shape of the membership function has on the outputted value of agility, various simulation runs have been performed. Figure 3 presents the variations of agility value

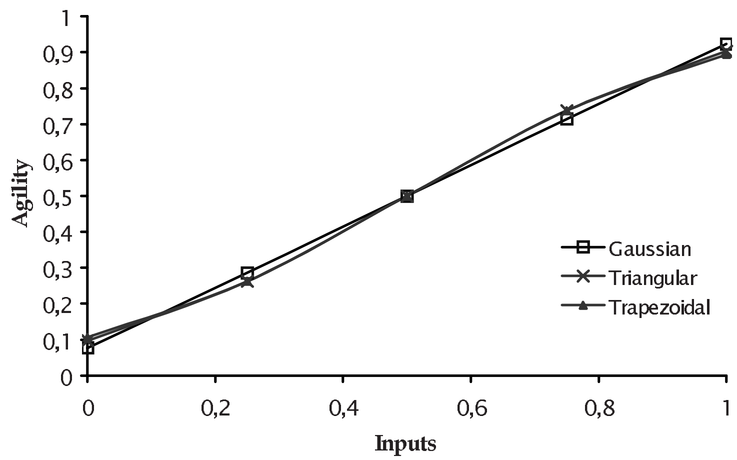

Figure 3. Agility measurements for different types of membership functions.

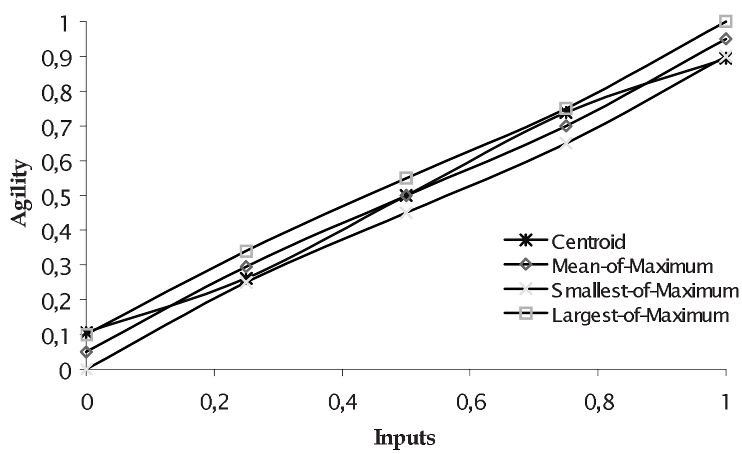

Figure 4. The Effect of defuzzification methods on agility measurements.

when using gaussian, triangular and trapezoidal membership functions. As can be seen, agility values are more or less the same for the three different shapes of memberships. The small variations that have been observed indicate that the significance of the membership function type in the proposed measuring methodology is limited.

The defuzzification method proved to be factor of increased significance for the measurement of agility. This is due to the important role of defuzzification in fuzzy logic systems. Figure 4 presents the observed variations of agility values for four different defuzzification methods, namely, *Centroid* (or Center-of-Area), *Mean-of-Maximum*, *Smallest-of-Maximum* and *Largest-of-Maximum*. It can be observed that the

P1: KMX/JXJ P2: KMX/GXL QC: KMX/GXL T1: GXL
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outputted agility values depend on the selected defuzzification method. This is a well known structural characteristic of the fuzzy logic based systems, thus, the selection of the defuzzification formula requires a close examination of the problem under study.

An extensive discussion on the selection of defuzzification methods can be found in [16].

6. CONCLUDING REMARKS

An agility measurement methodology based on the acquired knowledge, is described in this chapter. Knowledge is represented via linguistic IF-THEN rules, which has a number of clear advantages over other representation techniques.

The challenge in deriving agility measurements stems from the fact that parameters involved in the measurement of agility are not (or may not be) homogeneous. An additional difficulty in measuring agility is the lack of a one-to-one correspondence between agility factors and physical characteristics of the enterprise. As a result there exists inconsistent behavior of some parameters in the measurement of agility.

The chapter presents a novel and innovative effort to provide a solid framework for determining and measuring enterprise agility overcoming the above mentioned difficulties. The proposed measurement framework is direct, adaptive, holistic and knowledge-based. In order to calculate the overall agility of an enterprise, a set of quantitative agility parameters is proposed, defined with the aid of fuzzy logic and grouped into production, market, people and information infrastructures, all contributing to the overall agility measurement. From a technical point of view the proposed framework has the following advantages [14], [15], [18]:

1. It is adjustable by the user. Within the context of fuzzy logic, one can define new variables, values, or even rules and reasoning procedures. The model, therefore, provides a situation specific measurement and it is easily expanded.
2. It contributes to the acquisition and the representation of expertise concerning agility through multiple antecedent IF-THEN rules.
3. It provides successive aggregation of the agility levels as they are expressed through the already known agility types and, furthermore, incorporates types, which have not been widely addressed such as the agility of the workforce.
4. Can be easily implemented within a simulation testbed.

A topic of future research should be the examination of the relationship between the financial performances and the agility level measured in an enterprise. The results of such a study will be useful in determining how much agility is needed and to what extent it affects the profitability of a firm. Further, when one considers a company as a "whole entity" a topic that needs be studied is how the Research and Development sector contributes to the company's agility. Said differently, it is important to tackle how the quality of R&D and related activities, affects the overall agility measurement.

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