



On the Measurement of Enterprise Agility^{*}

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Abstract. Agility metrics are difficult to define in general, mainly due to the multidimensionality and vagueness of the concept of agility itself. In this paper, a knowledge-based framework is proposed and presented as a candidate solution for the measurement and assessment of manufacturing agility. Given an enterprise, in order to calculate its overall agility, a set of quantitatively defined agility parameters is proposed and grouped into production, market, people and information infrastructures. The combined, resulting, measure incorporates the individual and grouped infrastructure agility parameters and their variations into one calculated value of the overall agility. The necessary expertise used to quantitatively determine and measure individual agility parameters is represented via fuzzy logic terminology that allows for human-like knowledge representation and reasoning. An example demonstrates the feasibility and applicability of the proposed approach.

Key words: agility metrics, enterprise agility, agile manufacturing, fuzzy logic.

1. Introduction and Motivation

As market globalization raises competitive pressures worldwide, one essential requirement for enterprise survival is continuous ability to meet customer needs and demands. Market needs cause unceasing changes in product(s) life cycle, shape, quality, and price. Since the early 1980s, traditional methods of manufacturing large batches of products are no longer appropriate.

The term *agile manufacturing* gained wider recognition since the publication of the Iaccoca Institute's report "21st Century Manufacturing Enterprise Strategy" [5] and since then, manufacturing competitiveness has moved from the "era of mass production" to the "era of agility". As defined in [5, 8], 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.

However, application of agile manufacturing methods started in the late 1980s as a response of the (at the time) Western industry to competition from Japan

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and the other Pacific Rim area countries. Some of these methods include just-in-time manufacturing, flexible manufacturing systems, computer and communication networks. As a result, the U.S. Government started several programs and initiatives to help U.S. companies change their organization and production processes [8]. Such programs include the Department of Energy (DoE) *Demand Activated Manufacturing Architecture* [2] (textile/apparel industries), Technologies Enabling Agile Manufacturing (TEAM) [1], 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 [3].

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 [8]. The latter is one of the main differences between *agility* and *flexibility* in the business context. 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 [11], there does not exist a direct, adaptive and holistic treatment of agility components. In [4], 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 [6]. 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 [8], 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.

This paper is the outgrowth of the work presented by Tsourveloudis and Phillis in [12, 13] and it is further motivated by the need to remove the barrier associated with the derivation and implementation of a *synthesis method* that is sufficient to measure agility. 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 (composite or 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 paper is organized as follows. In Section 2, some general 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, we define four distinct agility infrastructures used for the measurement. Specific measuring variables are defined and explained. Section 4 gives a brief arithmetic example of the methodology. The paper concludes with discussion and a remarks section.

2. Modeling and Measurement Fundamentals

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.

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 [13]:

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. The measure is 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*.

2.1. PROPOSED DIVISIONS/INFRASTRUCTURES

The essential concept in agile manufacturing is the integration of organization, people, and technology into a coordinated interdependent system [8], 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:

- *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.

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).

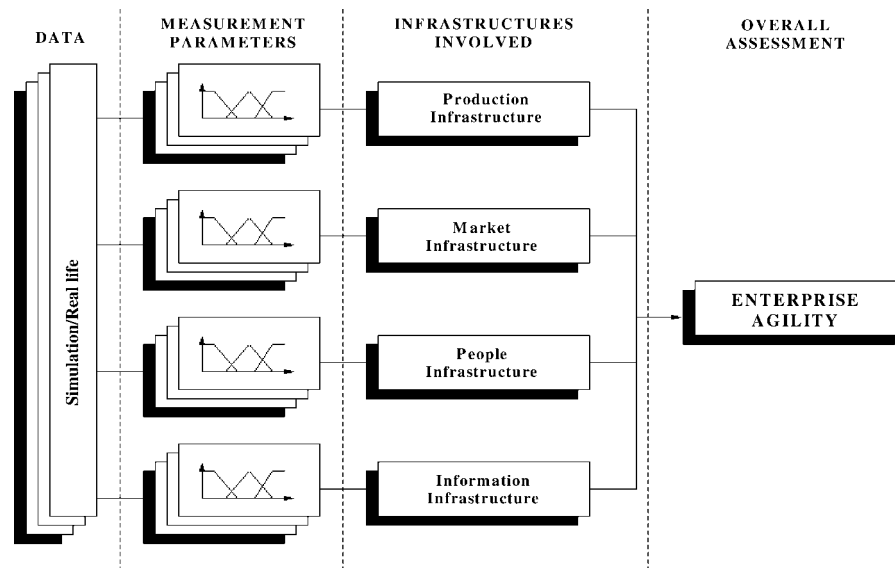


Figure 1. The architecture of the proposed assessment of agility.

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 $A_i, i = 1, \dots, N$, 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

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

or, in a compact representation, $(LA_1 \text{ AND } LA_2 \text{ AND } \dots \text{ AND } LA_N \rightarrow LG)$, 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 [15]. 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.

2.2. MATHEMATICAL FORMULATION

Let A_i , $i = 1, \dots, n$, be the parameters that indicate agility and can be used for its measurement. Each of the A_i 's takes linguistic variations LA_i^j , $j = 1, \dots, k$, and it is defined on U_i . LA_i^j 's are fuzzy sets defined as: $LA_i^j = \{(a_i, \mu_{LA_i^j}(a_i)) : a_i \in U_i\}$. The agility G of an enterprise, defined on $U_1 \times U_2 \times \dots \times U_n$, is given by

$$G = f(A_1, A_2, \dots, A_n), \quad (2)$$

where f represents the fuzzy or approximate reasoning procedure. In fuzzy logic terminology, the relation between agility and its observable parameters is expressed by fuzzy rules of the following form:

$$\text{IF } LA_1^j \text{ AND } LA_2^j \text{ AND } \dots \text{ AND } LA_n^j \text{ THEN } LG, \quad (3)$$

where LG is the set of the linguistic variations of agility. The rule in (3) can be rewritten as a relation equation in the membership functions domain:

$$\mu_R(a_1, \dots, a_n, g) = g_{\rightarrow} [\mu_{\text{AND}}(a_1, \dots, a_n), \mu_{LG}(g)], \quad (4)$$

where g_{\rightarrow} represents the fuzzy implication and $\mu_{\text{AND}}(a_1, \dots, a_n) = \mu_{LA_1^j}(a_1) \text{ AND } \dots \text{ AND } \mu_{LA_n^m}(a_n)$. The relation equation (4) is the mathematical interpretation of (3). One should select appropriate ‘AND’ (triangular norms), and implication operators for a given context. For example, if $\mu_A \text{ AND } \mu_B = \mu_A \wedge \mu_B$ and $g_{A \rightarrow B} = (1 - \mu_A) \vee \mu_B$, then (4) becomes

$$\mu_R(a_1, \dots, a_n, g) = \bigvee [1 - \mu_{LA_1^j}(a_1) \wedge \dots \wedge \mu_{LA_n^m}(a_n), \mu_{LG}(g)]. \quad (5)$$

For random values of LA_i^j , denoted by LA_i^{j*} (generally $LA_i^j \neq LA_i^{j*}$), the membership of the fuzzy set LG^* : “assessment of enterprise agility” is

$$\mu_{LG^*}(g) = \mu_{LA_i^{j*}} \circ \mu_R(a_1, \dots, a_n, g), \quad (6)$$

where ‘ \circ ’ represents the inference method, which may be either composition based, such as the *compositional rule of inference* derived by Zadeh [14], or individual-rule based inference. Note that LA_i^{j*} can be either crisp or fuzzy. The crisp value of agility g' , is the outcome of any defuzzification formula $def(\cdot)$:

$$def[\mu_{LG^*}(g)] = g'. \quad (7)$$

The real number given by (7) can be used easily for agility comparisons.

As already mentioned, the values at the various agility infrastructures are fuzzy sets with certain membership functions. New inputs/data O_i (observations) for the agility parameters activate the approximate reasoning procedure described above, which outputs a new value of agility g_i . The new unique pair $\langle O_i, g_i \rangle$ is stored in the knowledge base with the form of expression (3). In this manner the knowledge needed for the measurement is always updated.

3. Modeling of Agility Infrastructures

3.1. PRODUCTION INFRASTRUCTURE

Agility at the production infrastructure level allows for a quick reaction 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:

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 , $i = 1, \dots, 8$, 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:

$$\text{IF } T_1 \text{ is } LT_1 \text{ AND } \dots \text{ AND } T_8 \text{ is } LT_8 \quad \text{THEN } A_{\text{Prod}} \text{ is } LA_{\text{Prod}}, \quad (8)$$

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

3.2. 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 [7].

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:

$$\text{IF } T_1 \text{ is } LT_1 \text{ AND } \dots \text{ AND } T_4 \text{ is } LT_4 \quad \text{THEN } A_{\text{Market}} \text{ is } LA_{\text{Market}}, \quad (9)$$

where the notation in (9) follows that of (8).

3.3. 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 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 (8) and (9)):

$$\text{IF } W \text{ is } LW \text{ AND } J \text{ is } LT \text{ THEN } A_{\text{People}} \text{ is } LA_{\text{People}}. \quad (10)$$

3.4. 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* [10] 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.).
3. The generic fuzzy rule for this infrastructure can be written as follows (the notation is similar to (8)–(10)):

$$\text{IF } I \text{ is } LI \text{ AND } N \text{ is } LN \quad \text{THEN } A_{\text{Info}} \text{ is } LA_{\text{Info}}. \quad (11)$$

3.5. DISCUSSION

Table I 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, 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 $\langle\langle E, N, f \rangle\rangle$ exists [15].

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’ [15], which is an example of averaging operator giving values that range from the intersection to the union of the combined sets, as follows: $A \text{ AND } B = \gamma(A \cup B) + (1 - \gamma)(A \cap B)$. 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

Table I. 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 |

LJ THEN I_{people} is LI . The value of the conjunction (LW AND LJ) controls the level of LI . A pessimistic value ($\gamma = 0$) 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.

4. 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.

Assume that at a given time the agility parameters of an enterprise take the values presented in Table II. For the parameters that do not appear in Table II 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:

$$\text{Low} = L = \{(0, 1), (0.1, 1), (0.3, 0)\},$$

$$\text{Almost Low} = AL = \{(0.15, 0), (0.3, 1), (0.45, 0)\},$$

$$\text{Average} = A = \{(0.3, 0), (0.5, 1), (0.7, 0)\},$$

Table II. Data for the agility infrastructures

| Agility infrastructures | | | |
|--|--------------------------------------|--|------------------------------------|
| Production | Market | People | Information |
| $\langle S \text{ is Low} \rangle$ | $\langle P_S \text{ is Low} \rangle$ | $\langle W \text{ is Average} \rangle$ | $\langle I \text{ is Low} \rangle$ |
| $\langle V \text{ is High} \rangle$ | $\langle M_D = 0.5 \rangle$ | $\langle J \text{ is Low} \rangle$ | $\langle N \text{ is Low} \rangle$ |
| $\langle R = 0.8 \rangle$ | $\langle C_E \text{ is Low} \rangle$ | | |
| $\langle S_B = 0.7 \rangle$ | $\langle R_V \text{ is Low} \rangle$ | | |
| $\langle V_P \text{ is Average} \rangle$ | | | |

$$\text{Almost High} = AH = \{(0.55, 0), (0.7, 1), (0.85, 0)\},$$

$$\text{High} = H = \{(0.7, 0), (0.9, 1), (1, 1)\}.$$

The rules are of the Mamdani type [15] 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 $\langle S \text{ is } L \rangle$ AND $\langle V \text{ is } H \rangle$ AND $\langle R \text{ is } H \rangle$ AND $\langle S_B \text{ is } AH \rangle$ AND $\langle V_P \text{ is } A \rangle$
THEN $\langle A_{\text{Prod}} \text{ is } AH \rangle$,

IF $\langle S \text{ is } L \rangle$ AND $\langle V \text{ is } H \rangle$ AND $\langle R \text{ is } AH \rangle$ AND $\langle S_B \text{ is } AH \rangle$ AND $\langle V_P \text{ is } A \rangle$
THEN $\langle A_{\text{Prod}} \text{ is } AH \rangle$.

The fuzzy value of A_{Prod} is computed from (6). By applying the individual-rule based inference [14] the result is

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

Similarly, the membership functions of market, A_{Market} , people, A_{People} and information, A_{Info} , infrastructures are: $LA_{\text{Market}} = \{(0.15, 0), (0.3, 1), (0.45, 0)\}$, $LA_{\text{People}} = \{(0.15, 0), (0.3, 1), (0.45, 0)\}$, $LA_{\text{Info}} = \{(0, 1), (0.1, 1), (0.3, 0)\}$.

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 $\langle A_{\text{Prod}} \text{ is } AH \rangle$ AND $\langle A_{\text{Market}} \text{ is } AL \rangle$ AND $\langle A_{\text{People}} \text{ is } AL \rangle$ AND $\langle A_{\text{Info}} \text{ is } L \rangle$
THEN $\langle G \text{ is } AL \rangle$.

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 $LG = \{(0.15, 0), (0.25, 0.5), (0.35, 0.5), (0.45, 0)\}$.

5. Concluding Remarks

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 paper 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:

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 level of agility and the corresponding financial performance of enterprise. The results of such a study will be useful in determining how much agility is needed and to what extent it will affect the profitability of the enterprise. 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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