Measurement of Agility in Manufacturing Systems: A Fuzzy Logic Approach

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Abstract: Agility metrics are difficult to define, mainly due to the multidimensionality and vagueness of the concept of agility. In this paper, a fuzzy logic, knowledge-based framework is presented for the assessment of manufacturing agility. The combined measure incorporates certain operational parameters, their variations, and their effect on the value of agility. The necessary expertise used to quantitatively determine and measure agility is represented via fuzzy logic terminology, which allows for human-like knowledge representation and reasoning. Emerging standards for distributed simulation and virtual reality are utilised to implement a distributed simulation testbed. The testbed is used to simulate, measure, and evaluate agility and its parameters. The simulation testbed integrates the modeling of agility infrastructures, simulation of an enterprise through its infrastructures, real-life data, and a virtual reality based interface. High Level Architecture (HLA) and Virtual Reality Modeling Language (VRML) are standards selected for the implementation of the testbed.

Keywords: *Agility metrics, agile manufacturing, fuzzy logic, virtual reality testbed*

1 Introduction

Ever-changing is one of firms' major characteristics in this new competitive era. Agile manufacturing (AM) has been increasingly viewed as a winning strategy. AM is an integration of technologies, people, facilities, information systems and business processes.

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.*

Agile manufacturing is defined as *the capability of surviving and prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed high-quality, high-performance, products and services.* Critical to successfully accomplishing AM are a few enabling technologies such as the standard for the exchange of products (STEP), concurrent engineering, virtual manufacturing, component-based hierarchical shop floor control system, information and communication infrastructure, etc.

Managing Change

Agility is the outcome of technological achievement, advanced organizational and manageria1 structure and practice, but also a product of human abilities, skills, and motivations. The latter is one of the main difference 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. Flexible and computer integrated/aided manufacturing, total quality management, just -in-time manufacturing, concurrent engineering, etc., are enablers and components of an agile enterprise.

Due to the ill-defined and ambiguous criteria which exist with agility assessment, most measures are described subjectively, and the classical assessment approaches cannot suitably nor effectively be applied. However, fuzzy-logic is a very powerful tool to deal with vague and incomplete data. Thus the focus in this paper is development of an absolute agility index, a unique and unprecedented attempt in agility measurement, using fuzzy-logic.

In this paper, the value of agility is given by an approximate reasoning method taking into account the knowledge that is included in fuzzy IF-THEN rules. The methodology presented in the paper is analogous to the one suggested by Tsourvcloudis and Phillis (1998). It aims at providing the fundamentals of an adaptive knowledge-based methodology for the measurement of agility, which is then derived, implemented and tested in a simulation

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environment. The definition and derivation of a (composite or combined) agility measure is based on a group of quantitative metrics. By utilizing these measures (metrics), decision-makers have the opportunity to examine and compare different systems at different agility levels. We further discuss how emerging standards for distributed simulation and virtual reality may be used to implement a distributed simulation testbed, which will be used to simulate, measure and evaluate agility and its parameters. The challenge in deriving with the synthesis method stems from the fact that parameters involved in the measurement of agility may not be homogeneous. An additional challenge in measuring agility, is the lack of a one-to-one correspondence between agility factors and physical characteristics of the production system. As a result there exists inconsistent behavior of some parameters in the measurement of agility.

The rest of the paper is organized as follows: In Section 2, we present some general guidelines for the construction of any agility measure along with the characteristics and the mathematical. formulation of the proposed measurement methodology. The four distinct agility infrastructures we use in the measurement are given in Section 3. Section 4, describes briefly the simulation testbed, while clear concluding remarks are presented in the last section.

2 Manufacturing Agility

The concept that organizations must exhibit agility in responding to changing needs of the market was originally popularized by the US Agility Forum [Iacocca, 1991]. The prime task of the forum was to find solutions to declining productivity of American manufacturing in the face of rising challenge of international competition. Agility was suggested as the solution for restoring America's competitive edge in manufacturing. Agile manufacturing, as it was referred to, was an industry-led vision for a possible profound shift in the manufacturing.

2.1 Basic Characteristics

There is a growing body of literature on different aspects of agility, including a qualitative description of an agile enterprise [Goldman et al, 1995], operation of virtual enterprise using Fuzzy logic [Gupta and Nagi, 1995], the design and implementation of information system for agile manufacturing [Song and Nagi, 1997], design for agile assembly [Kusiak and He, 1997] and the use of business process redesign methodology [Burgess, 1994]. Others have focused on the difference between agile manufacturing and the earlier manufacturing paradigms.

The characteristics of an agile manufacturer include the following four ways of managing change:

- *Recognition* : The first step in managing change is to recognize that it is happening and proactively engage in change management. They can conduct a company-wide *knowledge audit*.

- *Focus on the customer*: Instead of allowing change to control your business, focusing on improving the customer's experience can be another way to control it. Customers want solutions that comprise both products and services, product flexibility and variability to meet their demands, and a quick response to questions that relate to pricing and support.

- *Leveraging resources:* An agile enterprise can also be recognized by its ability to successfully exploit its resources and share knowledge. Part of change management is to identify underutilized, unused or non-existent resources and take better advantage of them or bring them on board.

- *Cooperating to compete*: Finally, agile manufacturers change the way that they interact with their business partners so that they can compete more effectively through cooperation. They know that they do not dictate market demands: they listens to their customers, find core competence , make partnerships and share knowledge when it is necessary to provide the customer with a solution.

In view of the above statements, the *agility metric* will be:

1. **Direct:** it focuses on the observable operational characteristics that affect agility (direct measurement)
2. **Adaptive:** it provides context-specific measurements but without changing its structural characteristics every time. The measure will adapt to different manufacturing systems/enterprises
3. **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.
4. **Holistic:** it combines all known dimensions of agility

A. Infrastructures of Manufacturing Agility

We define (and explain in Section 3) the following divisions/infrastructures of manufacturing agility:

- **Production Infrastructure**
- **Market Infrastructure**
- **People Infrastructure**
- **Information Infrastructure**

The key idea of this methodology is to combine all infrastructures and their corresponding operational parameters to determine the overall agility. 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). 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 *Manufacturing* agility is *About Low*

where *Production, Market, People. Information* infrastructures and *Manufacturing agility* are the linguistic variables of the above rule, i.e. variables whose values are words such as, *LOW, Average, About Low* rather than numbers. These linguistic ratings are fuzzy sets with certain mathematical meaning represented by appropriate membership functions.

As the impact of all individual infrastructures on the overall manufacturing agility is hard to be analytically computed, we devise fuzzy rules to represent the accumulated human expertise. To explain the structure of fuzzy rules and the fuzzy formalism to be used towards measurement, consider that A_i, $i= 1\ldots\ldots N$, is the set of agility divisions and *LV*, the linguistic value of each division. Then, the expert rule is

$$\text{IF } A_1 \text{ is } LV_1 \text{ AND... AND } A_N \text{ is } LV_N \text{ THEN } A_{MA} \text{ is } MA \quad (1)$$

or, in a compact representation,
$(LV_1 \text{ AND } LV_2) \text{ AND ... AND } LV_N \rightarrow MA)$,
where *MA* represents the set of linguistic values for manufacturing agility A_{MA}. All linguistic values LV_1 and *MA* are fuzzy sets, with certain membership functions. 'AND' represents the fuzzy conjunction and has various mathematical interpretations within the fuzzy logic literature. 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. Let, now, $D = LV_1$ AND LV_2 AND ... AND LV_N. Then (1) becomes

$$\text{IF } (A_1, A_2, \ldots A_N) \text{ is D THEN } A_{MA} \text{ is } M \quad (2)$$

or just $D \rightarrow MA$, where $(A_1, A_2, \ldots A_N)$ is called the *joint variable* and represents the combined effect of the allocated divisions/infrastructures on agility.
The fuzzy relation *L* induced by (2) is

$$L_{D\rightarrow MA}(x, y) = f_{\rightarrow}[d(x), ma(y)] \quad (3)$$

where $f_{\rightarrow}$ is the functional form of the *fuzzy implication*, *d(x)* is the membership function of the conjunction *D*, and *ma(y)* is the membership function of *MA*. Equation (3) is the mathematical interpretation of a fuzzy rule and leads to the construction of an *implication matrix*, which maps the fuzzy knowledge described by the rule.

The inputs to the described rules, i.e. the assessments of agility infrastructures, are fuzzy sets which, in general, are different from the *LVi's* included in the rule base. Consequently the conjunction of these sets differs from *D*. Manufacturing agility is then computed from

$$MA' = D' \text{ o } L_{D\rightarrow MA} \quad (4)$$

where "o" represents an *approximate reasoning* procedure (Zadeh, 1979) *MA'* is the deduced value of agility and *D'* is the conjunction of inputs. In the membership functions domain the value of agility is given by the following equation:

$$ma'(y) = d'(x) \text{ o } f_{\rightarrow}[d(x), ma(y)] \quad (5)$$

where, *ma'(y)*, *d'(x)*, *ma(y)* and *d(x)* are the membership functions of *MA'*, *D'*, *MA*, and *D*, respectively.
In order to provide a direct measurement of the overall agility one needs to know the agility value of each one of the infrastructures.

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 In order to achieve agility in the production infrastructure(*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.*Setup or changeover time and cost* (S) required for various preparations such as tool, or part positioning and release, software changes etc.

2.*Versatility* (V) which is defined as the variety of operations a machine/workstation is capable of performing.

3 *Range of adjustments or adjustability* (R) of a machine which is defined as the size of working space and is related

ISBN:978-988-17012-3-7

to the maximum and minimum dimensions of the parts that the machine can handle.

4.*Substitutability* (S_B) which is the ability of a production system to reroute and reschedule jobs effectively under failure conditions.

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 n material handling system carries. It is restricted by the volume dimension, and weight requirements of the load.

7.*Transfer speed*(C), which is associated with the weight and geometry of products, as well as the frequency of transportation.

8.Part Variety (V_P) is associated with the number of new product, the manufacturing system is capable of producing in a time period without major investments in machinery.

9. *Changeover effort* (S_P) 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 market variations.

10. *Part commonality* (C_P) 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.

These parameters are not always independent. Linguistic or fuzzy rules overcome this problem by involving already known facts into the measurement procedure. Specifically, let T_i, i =1, ….., 10, denote the set of parameters of concern, such that LT_i, are the linguistic values of T_i s. The rule, which represents the expert knowledge on how the all the above mentioned parameters affect the production agility A_{Prod} is

$$\text{IF } T_1 \text{ is } LT_1 \text{ AND ... AND } T_{10} \text{ is } LT_{10} \text{ THEN } A_{Prod} \text{ is } LA_{Prod} \quad (6)$$

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

3.2 Market Infrastructure

At the level of market infrastructure, agility is characterized by the ability to identify market opportunities, to develop short-lifetime, customizable products and services and to deliver them in varying volumes more quickly and at a lower price. The parameters identified for the measurement of the agility (A_{Market}) of the market infrastructure are:

1.*Reconfigurability* (P_S) of the product mix is the set of part types that can be produced simultaneously.

2.*Modularity index*(M_D), which represents the ease of adding new customized components without significant effort.

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.

The generic measuring rule for the agility of this infrastructure, may be as follows

$$\text{IF } T_1 \text{ is } LT_1 \text{ AND ... AND } T_4 \text{ is } LT_4 \text{ THEN } A_{Market} \text{ is } L\, A_{Market} \quad (7)$$

where the notation in (7) follows that of (6).

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 expressions of moving towards agility. The variables defined as agility level indicators of this infrastructure (A_{People}), are

1.*Training level* (W). Personnel training contribute 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

$$\text{IF W is } LW \text{ AND J is } I.T \text{ THEN } A_{People} \text{ is } L\, A_{People} \quad (8)$$

3.4 Information Infrastructure

The information infrastructure plays the critical role in the development of the agile capabilities, especially in the context of global and distributed organizations. The concept of *multi-path agility* (Sanderson et al., 1994) used to improve productivity and response time. The variables indicating the information infrastructure agility (A_{Info}) are:

1.*Interoperability* (I) is a measurement of a level of standardization provides an indication of the information infrastructure agility.

2.*Networking (*N) includes the communication capabilities of an enterprise are defined through ability to exchange information.
The generic fuzzy rule for this infrastructure can be written as follows

IF I is LI AND N is LN
THEN A_{Info} is LA_{Info} (9)

4 Simulation Testbed

The proposed testbed is used to simulate, measure and evaluate agility and its parameters. Applications of virtual reality for simulation and testing of agile manufacturing have been reported by Lefort and Kesavadas (1998), Subbu et al. (1998), and other researchers. The two core standards used include:

1. High Level Architecture (HLA): facilitates reuse of simulation and their components by specifying the general structure of the interfaces between simulations without making specific demands on the implementation of each simulation. The whole distributed application (exercise, set of simulations) is called a federation. The four basic concepts include:

(i) Run-Time Infrastructure (RTI): Implementation of a distributed operating system as a base software layer that manages communication between all simulation models, (ii*) Rules:* A set of ten technical rules to which an HLA participant has to comply, (iii)*Interface Specification:* Formal, functional description of the interface between the HLA application and the Run-Time Infrastructure (RTI), and (iv) *Object Model Templates*: Standardized formats used to specify the functionality of simulation models and interaction among them before the actual simulation takes place.

2. **Virtual Reality Modeling Language (VRML):** has introduced three dimensional (3D) graphical visualization and interactivity to the Internet and the World Wide Web (WWW). The current international Standard for VRML, ISO/IEC 14772-1:1997, VRML97, provides a means for creating static and animated 3D multimedia objects/worlds, user interaction, scripting, and prototyping.

5. Concluding Remarks

The paper gives effective framework in showing increased performance by using fuzzy techniques and also in giving a systematic design procedure that takes into account multiple objectives and needs no interface with linguistic directions from human experts (e.g., management). It provides an innovative effort to provide a solid framework for determining and measuring enterprise agility in terms of a (potentially and easily modifiable or expanding) list of quantitatively defined parameters. The proposed measurement framework is direct, adaptive, holistic and knowledge-based. In order to calculate the overall agility of an enterprise, a set of quantitatively are defined agility parameters is proposed 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.
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
4.Can be easily implemented within a virtual reality based simulation testbed.
5.It helps in Management planning and execution tools. This involves the use of techniques as manufacturing resource planning, real-time manufacturing execution systems, production planning configurators, and real-time threaded scheduling through Fuzzy Logic approach.
6. Contributes to Business process reengineering by Intraorganizational and Interorganizational cooperation and use of information technology to measure and manage agility and flexibility in manufacturing systems.

A topic of future research should be the examination of the relationship between the level of agility and the corresponding financial performance of enterprise. Flexibility provided by agility may emerge as the most important competitive priority of the early twenty-first century, as competition is expected to ensure that manufacturers will increasingly need to adapt readily to market shifts. 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.

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