# FUZZY MODELING AND MEASUREMENT OF MANUFACTURING FLEXIBILITY

**D.Mishra* and B.B.Biswal**
Department of Mechanical Engineeing
University College of Engineering, Burla
Sambalpur, Orissa, India, PIN-768018

**Abstract** Manufacturing flexibility is an effective tool to face up to the uncertainties put forth by the rapidly changing environment. There are a number of parameters of manufacturing flexibility, which are difficult to be treated simultaneously for quantification of the overall manufacturing flexibility of a system that can be looked upon as consisting of a number of flexibility types such as machine flexibility, routing flexibility, product flexibility etc. The nature of flexibility varies so greatly that it is difficult to take care of the problem through deterministic or mathematical models. In the present paper, an approach for measuring manufacturing flexibility is presented in which all the parameters needed in various steps in the quantification procedure are represented by words and overall flexibility is given by their synthesis. The proposed system uses expert knowledge, fuzzy logic methods and terminology to assess manufacturing flexibility.

*Keywords: Manufacturing flexibility, knowledge based measurement, fuzzy logic*

## INTRODUCTION

Flexibility is a desirable property of production systems, which quite often is presented as a panacea to numerous practical problems. The development of flexibility measure is extremely useful in order to exploit the benefits of a flexible system. By utilizing these measures, decision makers have the opportunity to examine different systems at different flexibility levels. This objective seems elusive, unless measures provide a direct and holistic treatment of flexibility components. As manufacturing systems are operated and managed by people, it is necessary to record and utilize human knowledge perceptions about flexibility in its measurement [Gupta, Y.P. *et al*., 1992]. Regardless of the structure of each measure, it is important to establish basic principles, which should be satisfied by any flexibility measure.

In the present study, an approach for measurement of manufacturing flexibility is described, in which all parameters needed in the various steps of the quantification procedure are represented by words and the overall flexibility is given by their synthesis. The system uses expert knowledge and consists of an implementation of fuzzy logic methods and terminology to assess manufacturing flexibility [Tsourveloudis, N.C. *et al*., 1998].

## KNOWLEDGE-BASED MEASUREMENT

Manufacturing flexibility exhibits a polymorphism that makes quantification a difficult exercise. Direct measures of flexibility utilize operational parameters, which determine the flexibility type in contrast to measures that focus on the economic or performance consequences of flexibility. Sometimes flexibility parameters cannot be accurately defined. In addition, a sufficient synthesis method of the operational parameters of flexibility is lacking. The reasons are non-homogeneity in the parameters involved in the measurement and lack of a one-to-one correspondence between flexibility types and the physical characteristics of the production system. As a result, there is inconsistent behaviour of some parameters in the measurement of flexibility [Gupta, D. *et al*., 1989]. It is important to take into account the expert knowledge about the quantification of the observable parameters of the notion as mathematical models have difficulties in dealing with the direct measurement of flexibility. A knowledge-based measurement can be achieved by suitable representation of the human expertise, concerning the combination of the flexibility parameters, which overcome these problems. Fuzzy logic offers a methodological framework to represent knowledge together with a reasoning procedure whereby the value of flexibility is deduced [Zadeh,L.A. 1983].

### Fuzzy Expert System

A fuzzy expert system is a collection of membership functions and rules that are used to reason about data

Email: *mishra_dm@rediffmail.com

and are oriented toward numerical processing. The process of application of expert knowledge, with the definition of the rules and membership to specific values of the input variables to compute the values of the output variables is referred to as inferencing. In a fuzzy expert system, the inference process is a combination of four subprocesses: (a) fuzzification, (b) inference, (c) composition, and (d) defuzzification.

**(a) Fuzzification**

In the fuzzification subprocess, the membership functions defined on the input variables are applied to their actual values, to determine the degree of truth for each rule premise.

**(b) Inference**

In the inference subprocess, the truth-value for the premise of each rule is computed, and applied to the conclusion part of each rule. This results in one fuzzy subset to be assigned to each output variable for each rule. There are two inference methods or inference rules: MIN and PRODUCT. In MIN inferencing, the output membership function is clipped off at a height corresponding to the rule premise's computed degree of truth. In PRODUCT inferencing, the output membership function is scaled by the rule premise's computed degree of truth.

**(c) Composition**

In the composition subprocess, all of the fuzzy subsets assigned to each output variable are combined together to form a single fuzzy subset for each output variable. There are two familiar composition rules: MAX composition and SUM composition. In MAX composition, the combined output fuzzy subset is constructed by taking the pointwise maximum over all of the fuzzy subsets assigned to the output variable by the inference rule. In SUM composition the combined output fuzzy subset is constructed by taking the pointwise sum over all of the fuzzy subsets assigned to the output variable by the inference rule. This can result in truth-values greater than one. Therefore, SUM composition is only used when it will be followed by a defuzzification method.

**(d) Defuzzification**

In the defuzzification subprocess the fuzzy values are converted to a single number - a crisp value. There are more than thirty defuzzification methods. Two of the more common techniques are the CENTROID and MAXIMUM methods. In the CENTROID method, the crisp value of the output variable is computed by finding the variable value of the center of gravity of the membership function for the fuzzy value. In the MAXIMUM method, one of the variable values at which the fuzzy subset has its maximum truth-value is chosen as the crisp value for the output variable.

## MODELLING AND MEASUREMENT OF FLEXIBILITY

The key idea of the model in this study is the involvement of the distinct types of flexibility and corresponding operational parameters in the determination of the overall flexibility. This is implemented via multi-antecedent fuzzy IF-THEN rules, which are conditional statements that relate the observations concerning the allocated types (IF part) with the value of flexibility (THEN part). These rules are efficient way to map input spaces to output spaces, especially when the physical relationship between these spaces is too complex to be described by mathematical models. Considering the impact of operational parameters on the individual flexibility and also the impact of individual flexibility types on the overall flexibility, fuzzy rules have been devised to represent the accumulated human expertise. In other words, the knowledge concerning flexibility, which is imprecise or even partially inconsistent, has been used to draw conclusions about the value of flexibility by means of simple calculus.

Suppose that $P_i$, i =1,….N, is the set of operational parameters for a particular flexibility type and $A_i$ the linguistic value of each parameter, then the expert knowledge general rule for computing individual flexibility is;

**IF** $P_i$ is $A_i$ AND …….. $P_N$ is $A_N$ **THEN** $P_{XF}$ is $XF$ (1)

or

$(A_1 \text{ AND } A_2 \text{ AND } \ldots\ldots \text{ AND } A_N) \rightarrow XF$ (2)

where, $XF$ represents the set of linguistic values for a flexibility type $P_{XF}$.

Further, let $F_i$, i = 1,…,N, is the set of flexibility types and $B_i$ be the linguistic value of each type, then the expert general rule for computing overall flexibility is;

**IF** $F_i$ is $B_i$ AND …….. $F_N$ is $B_N$ **THEN** $F_{MF}$ is $MF$ (3)

or

$(B_1 \text{ AND } B_2 \text{ AND } \ldots\ldots \text{ AND } B_N) \rightarrow MF$ (4)

All linguistic values $A_i$ & $B_i$ and $XF$ & $MF$ are fuzzy sets defined by a membership function on the base sets $X$ and $Y$ such that $a_i(x)$ and $xf(y)$ denote the membership grades of element x and y in $A_i$ and $XF$ respectively and $b_i(x)$ and $mf(y)$ denote the membership grades of element x and y in $B_i$ and $MF$ respectively. "AND" represents the fuzzy conjunction, which is the intersection of fuzzy sets, corresponding to a whole class of triangular or T-norms [Dubois, D. *et al.*, 1982]. The selection of the logical connective "AND", in the flexibility rules, is based on empirical testing and other criteria [Zimmerman, H.J., 1991] within a particular setup, as flexibility means different things to different people.

Let, now, $D = A_1$ AND $A_2$ AND …… AND $A_N$. Then, (2) becomes;

IF ($P_1, P_2, \ldots, P_N$) is $D$ THEN $P_{XF}$ is $XF$ (5)

where, ($P_1$, $P_2$, ….., $P_N$ ) is called the joint variable which, represents the combined effect of the allocated types of parameters on the individual flexibility. The fuzzy relation $L$ induced by (5) is;

$$L_{D \to XF}(x,y) = f_{\to}[d(x), xf(y)] \quad (6)$$

Similarly, let $C = B_1$ AND $B_2$ AND …….. AND $B_N$. Then (4) becomes

IF ($F_1$, $F_2$, …. $F_N$) is $C$ THEN $F_{MF}$ is $MF$ (7)

where, ($F_1$, $F_2$, ….., $F_N$ ) is called the joint variable which, represents the combined effect of the allocated flexibility types. The fuzzy relation $L$ induced by (7) is;

$$L_{C \to MF}(x,y) = f_{\to}[d(x), xf(y)] \quad (8)$$

Where, $f_{\to}$ is the functional form of the fuzzy implication and $d(x)$ is the membership function of the conjunction $D$. Equations (6) & (8) are 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. Any implication and conjunction operators can be used to achieve the desirable knowledge representation within the given context.

The inputs to the described rules are fuzzy sets, which, in general, may be different from $A_i$'s & $B_i$'s included in the rule base. Consequently the conjunctions of these sets differ from $D$ and $C$. Flexibilities are then calculated from the following relations;

$$XF' = D'^{0} L_{D \to XF} \text{ and } MF' = C'^{0} L_{C \to MF} \quad (9)$$

where, '0' represents an approximate reasoning procedure [Zadeh, L.A., 1979], *XF*' and *MF*' are the deduced value of flexibilities and *C*' & *D*' are the conjunction of inputs. Fuzzy reasoning is used to draw a conclusion from an observation that does not match exactly with the antecedents.

**MODELLING AND SIMULATION OF THE FMSs**

In the present study, three setups have been considered. Setup-1 consists of two CNC lathes and two CNC machining centers well connected by suitable conveying system. In setup-2, a CNC drilling machine replaces a machining center of setup-1 and in setup-3, a second CNC drilling machine replaces the other CNC machining center in setup-1. Three different products have been chosen for manufacture with all the setups. The products belong to the same group from the viewpoint of group technology, as their design attributes as well as manufacturing attributes are similar. The setups have been modeled in QUEST, a 3D graphics based queuing event simulation tool with realistic input data and the results so obtained have been used for assessment of manufacturing flexibility.

**FUZZY MODELING OF FLEXIBILITY TYPE**

Manufacturing flexibility, as stated earlier, is multidimensional and therefore, has been broken down into several distinct types. Some of them are widely accepted as the most important for the explanation and determination of manufacturing flexibility. In the sequel, a knowledge based measuring scheme concerning machine, routing, process, product and material handling has been dealt with in the present study.

Knowledge acquisition can be achieved by using various methodologies such as questionnaire or existing surveys etc [Gupta, Y.P. *et al*., 1992]. In the present study, the results obtained from simulation of different setups, which are analogous to the real time data, have been utilized to assign weightage to different variables. Thus, it is important to mention here that, the measurement scheme depends on the expertise regarding the variables. The fundamental assumptions of the measuring methods are:

1. Manufacturing flexibility, which is an inherently fuzzy notion, is measured by the synthesis of its constituents.

2. The measurement is assumed to take into account the particular characteristics of the setup under study.

In the present study, the linguistic values for the input variables of the flexibility types and also that for the flexibility output have been expressed as *High*, *Medium* and *Low* for implementation of fuzzy rules, in all the setups. The membership function for the variables is shown in Fig.1. The fuzzy rules are framed with the help of expert knowledge acquired during the simulation of the setups. As listing down of all the rules are beyond the scope of this paper some of these rules have been mentioned under each flexibility type.

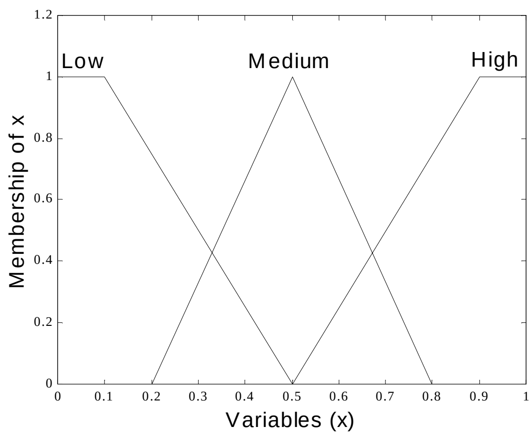


**Fig. 1 Membership function of the linguistic variables**

**Machine flexibility**

Machine flexibility (*MF*) is the simplest kind of flexibility that can be defined in a manufacturing system and constitutes a necessary building block for the assessment of the overall flexibility. Modern machines are equipped with tool changing mechanisms which enable the machines to perform several operations in a given configuration with reduced loading, unloading and tool changing times. The parameters, that have been used in the computation of machine flexibility are (a) changeover time (*CT*); the time required for various preparations such as tool or part positioning, release etc. and (b) versatility (*V*); the variety of operations a machine is capable of performing [Tsourveloudis, N.C., *et al*., 1997].

***Fuzzy Rules***

IF *CT* is *Low* AND *V* is *High* THEN *MF* is *High*
IF *CT* is *High* AND *V* is *Low* THEN *MF* is *Low*
IF *CT* is *High* AND *V* is *High* THEN *MF* is *Medium*

***Variables' Weight***

*Changeover time* (*CT*): Weightage to this variable in the different setups are assigned by considering the individual changeover times with respect to the number of changeovers taking place in all the machines in all the routes for all the products.

*Versatility* (*V*): It is weighed by considering the number of operations performed by different machines in a setup and the total number of operations to be performed for different products under consideration.

**Routing flexibility**

Routing flexibility (*RF*) allows for a quick reaction to unexpected events such as machine breakdowns and minimizes the effect of interruptions of the production process. Routing flexibility arises from the existence of interchangeable machines, capable of performing similar operations. The ability to handle breakdowns, which is the main characteristics of routing flexibility, exists if each operation can be performed on more than one machine. The key prerequisite in measuring routing flexibility is the ability of a machine to substitute for another. The linguistic variables that have been defined for the assessment of routing flexibility are (a) processing time (*PT*); the time taken for completion of a process and (b) route substitution (*RS*); the ability of a system to reroute and reschedule jobs effectively under failure conditions [Tsourveloudis, N.C., *et al*., 1997].

***Fuzzy Rules***

IF *PT* is *High* AND *RS* is *Low* THEN *RF* is *Low*
IF *PT* is *High* AND *RS* is *High* THEN *RF* is *Medium*
IF *PT* is *Low* AND *RS* is *High* THEN *RF* is *High*
IF *PT* is *Low* AND *RS* is *Low* THEN *RF* is *Medium*
IF *PT* is *High* AND *RS* is *Medium* THEN *RF* is *Low*

***Variables' Weight***

*Processing time* (*PT*): This parameter is evaluated by considering the processing time for each operation in the different machines with respect to all the products in all the routes.

*Route substitution* (*RS*): The weightage to this parameter has been assigned by identifying the alternate routes in all the setups. The route substitution factor is determined by the ratio of the number of alternate routes to the total number of feasible routes.

**Process flexibility**

Process flexibility (*PRF*) is a result of the ability of a manufacturing system to produce different types of products at the same time. It helps in reducing the batch sizes and minimizes work-in process, buffer sizes and inventory costs. In order to achieve process flexibility, a combination of certain desirable characteristics like, the skill level of workers, usage of multipurpose machines and fixtures, redundant equipment, material handling devices and process variety is needed. Here, the linguistic variables of concern are (a) processing operations (*PO*); operations that need to be performed for manufacturing a product on particular machine in the setup, (b) processing skill (*PS*); the skill of the worker or the precision of the machine that is required for processing a product on a machine, (c) processing time (*PRT*); the time taken for completion of a process for a product on a particular machine in the setup and (d) physical nature (*PN*); the shape and size of the products to be processed in the setup [Das, S.K., 1996].

***Fuzzy Rules***

IF *PO* is *Low* AND *PS* is *High* AND *PRT* is *Low* AND *PN* is *Low* THEN *PRF* is *High*
IF *PO* is *High* AND *PS* is *Low* AND *PRT* is *High* AND *PN* is *High* THEN *PRF* is *Low*
IF *PO* is *High* AND *PS* is *High* AND *PRT* is *High* AND *PN* is *High* THEN *PRF* is *Low*
IF *PO* is *Low* AND *PS* is *Low* AND *PRT* is *Low* AND *PN* is *Low* THEN *PRF* is *High*

***Variables' Weight***

*Processing operations* (*PO*): This parameter has been weighed on the basis of the difference in processing operations to be performed on the products at a machine which is evaluated by looking at the data on the range of operations that each machine performs.

*Processing skill* (*PS*): This factor has been evaluated by focussing on the different skill required between the products at a machine. The difference in skill requirement has been assessed by considering the ratio of the number of uncommon operations requiring different skill between the products on a machine and the master list of operations with respect to skill.

*Processing time* (*PRT*): The weights of this variable have been assessed on the basis of the difference in processing time for different products on a route.

*Physical nature* (*PN*): This parameter has been weighed by considering both manufacturing and design attributes consistent with the shape and size of the products. The weight for this parameter has been taken as the average value of product difference on a machine with respect to different products.

**Product flexibility**

Product flexibility (*PDF*) is associated with the number of products that are produced by the manufacturing system in the period of interest. This helps the firm respond to demand changes and increase productivity by introducing new products in the market quickly. Parameters pertinent to the measurement of product flexibility are (a) set up cost (*SC*); the cost of tooling, reprogramming and retraining and also the cost of down time due to setting up and (b) set up time (*ST*); the time required for tool changing, reprogramming and retraining [Das, S.K., 1996].

***Fuzzy rules***

IF *SC* is *High* AND *ST* is *High* THEN *PDF* is *Low*
IF *SC* is *High* AND *ST* is *Low* THEN *PDF* is *Medium*
IF *SC* is *Low* AND *ST* is *High* THEN *PDF* is *Medium*

***Variables Weight***

*Set up cost* (*SC*): This parameter has been evaluated by considering the set up cost involved by the introduction of a new and different product to the setup, with respect to the maximum allowable set up cost. The maximum amount that can be spent [Das, S.K., 1996] with respect to the actual amount spent for set up has been taken as the weightage of this parameter.

*Set up time* (*ST*): This parameter has been weighed by considering the cost incurred due to the setup downtime needed for set up during introduction of a new and different product. Weights for this parameter has been evaluated by taking the ratio of actual value added time to the maximum value added time that can be spent for setting up of the setup for introduction of a new and different product.

**Material handling flexibility**

Material handling flexibility (*MHF*) associated with movement of different part types efficiently for proper positioning and processing through the manufacturing setup. This flexibility is dependent to the material handling system's versatility and responsiveness to a great extent. Parameters considered for measurement of this flexibility are (a) move time; the time taken by the material handling system to transfer a part from one machine to another on a path, (b) number of machines; the machines at which the material is to be processed and between which material handling would take place, and (c) number of available paths; the maximum number of paths on a route [Das, S.K., 1996].

***Fuzzy rules***

IF *MT* is *High* AND *NM* is *High* AND *NP* is *High* THEN *MHF* is *Low*
IF *MT* is *Low* AND *NM* is *Low* AND *NP* is *Low* THEN *MHF* is *high*
IF *MT* is *Medium* AND *NM* is *Medium* AND *NP* is *Medium* THEN *MHF* is *Medium*
IF *MT* is *High* AND *NM* is *Low* AND *NP* is *Medium* THEN *MHF* is *Medium*
IF *MT* is *Medium* AND *NM* is Low AND *NP* is *High* THEN *MHF* is *High*

***Variables weight***

*Move time* (*MT*): This parameter has been weighed by considering the time taken by the material handling system to transfer parts form one machine to another in different routes. The average of difference in move time for all the products in different routes has been considered for computation of this weightage.

*Number of machines* (*NM*): This factor is weighed on the basis of the number of machines the material handling equipment visits for accomplishing a product in different routes. This has been evaluated by considering the number of machine used for processing with respect to all the products in all the routes.

*Number of available paths* (*NP*): This variable is assessed by taking the ratio of the total number of available paths to the total number of feasible paths for accomplishing different products in all the routes.

**Overall Manufacturing Flexibility**

The measurement of different flexibility types, observed in different hierarchical levels of the setups, discussed above has been utilized to find out the overall manufacturing flexibility (*OMF*). The methodology adopted is same as that applied in assessment of individual flexibility types. Overall manufacturing flexibility has been found out by the logical synthesis of the flexibility types already examined and the same is depicted in Fig. 2.

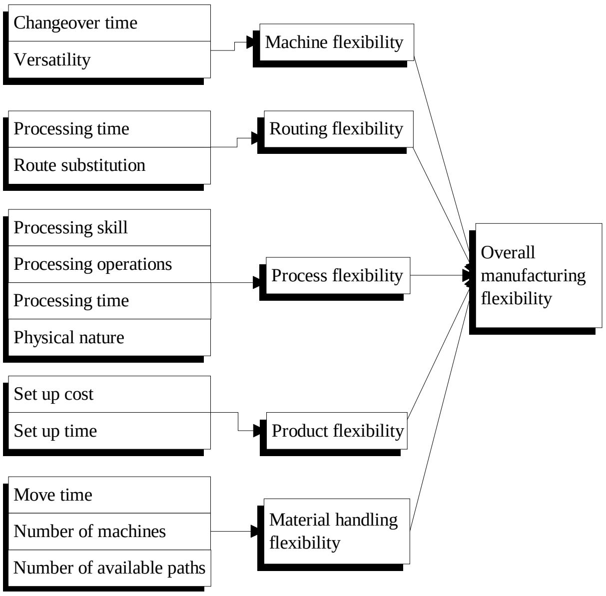


**Fig. 2 Fuzzy assessment of overall manufacturing flexibility**

The logical synthesis is expressed by IF-THEN fuzzy rules. The expert rules are drawn on the basis of the expertise gained during simulation of the FMSs in virtual environment as described earlier.

***Fuzzy rules***

IF *MF* is *High* AND *RF* is *High* AND *PRF* is *High* AND *PDF* is *High* AND *MHF* is *High* THEN *OMF* is *High*
IF *MF* is *Medium* AND *RF* is *Medium* AND *PRF* is *Medium* AND *PDF* is *Medium* AND *MHF* is *Medium* THEN *OMF* is *Medium*
IF *MF* is *Low* AND *RF* is *Low* AND *PRF* is *Low* AND *PDF* is *Low* AND *MHF* is *Low* THEN *OMF* is *Low*
IF *MF* is *High* AND *RF* is *High* AND *PRF* is *High* AND *PDF* is *High* AND *MHF* is *Low* THEN *OMF* is *High*
IF *MF* is *High* AND *RF* is *High* AND *PRF* is *Low* AND *PDF* is *Low* AND *MHF* is *Low* THEN *OMF* is *Low*
IF *MF* is *High* AND *RF* is *High* AND *PRF* is *High* AND *PDF* is *Low* AND *MHF* is *Low* THEN *OMF* is *Medium*
IF *MF* is *High* AND *RF* is *High* AND *PRF* is *High* AND *PDF* is *Medium* AND *MHF* is *Medium* THEN *OMF* is *High*

***Variables weight***

The flexibility values obtained from fuzzy calculation of different flexibility types by fuzzy logic method have been given as the input to the fuzzy inference engine for finding out the overall manufacturing flexibility. The weights of different variables for measurement of individual flexibility type, for all the three setups under consideration in the present study have been presented in Table-1.

**Table-1: Weights of variables for each flexibility type for all setups**

| Types of flexibility | Variables | Assessed weights | | |
|---|---|---|---|---|
| | | Setup-1 | Setup-2 | Setup-3 |
| Machine flexibility | Changeover time | 0.47 | 0.45 | 0.50 |
| | Versatility | 0.62 | 0.60 | 0.45 |
| Routing flexibility | Processing time | 0.47 | 0.42 | 0.49 |
| | Route substitution | 0.66 | 0.66 | 0.66 |
| Process flexibility | Processing operations | 0.45 | 0.43 | 0.38 |
| | Processing skill | 0.31 | 0.30 | 0.31 |
| | Processing time | 0.34 | 0.31 | 0.35 |
| | Physical nature | 0.32 | 0.30 | 0.27 |
| Product flexibility | Set up cost | 0.80 | 0.71 | 0.76 |
| | Set up time | 0.83 | 0.69 | 0.78 |
| Material handling flexibility | Move time | 0.80 | 0.40 | 0.38 |
| | Number of machines | 0.37 | 0.37 | 0.37 |
| | Number of paths | 0.58 | 0.50 | 0.50 |

## RESULTS

A fuzzy program for determination of manufacturing flexibility has been written in MATLAB and it has been run using the assessed weights as input. The values of the flexibility types and the overall manufacturing flexibility obtained from the program are presented in Table-2.

**Table-2: Values of flexibility**

| | *MF* | *RF* | *PRF* | *PDF* | *MHF* | *OMF* |
|---|---|---|---|---|---|---|
| Setup-1 | 0.64 | 0.38 | 0.63 | 0.50 | 0.50 | 0.50 |
| Setup-2 | 0.63 | 0.48 | 0.62 | 0.32 | 0.62 | 0.48 |
| Setup-3 | 0.45 | 0.32 | 0.63 | 0.44 | 0.64 | 0.40 |

## CONCLUSIONS

The accurate quantification of flexibility through any deterministic approach is a cumbersome act. The factors influencing the flexibility are overlapping, varying in nature and sometimes unclear. Most of the factors of flexibility are either due to the human involvement or situation based. On the other hand, the fuzzy approach takes care of the uncertainties and is more convenient. However, appropriate care should be taken while assessing the weights of the variables and selecting the membership function. The overall manufacturing flexibility increases with inclusion of more numbers of flexible machines, which is evident from the overall flexibility value of setup-1, where the machine flexibility is the maximum. Out of the flexibility types, machine flexibility, process flexibility and material handling flexibility are the most predominant ones.

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