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Rejuvenating the Supply Chain by Benchmarking using Fuzzy Cross-Boundary Performance Evaluation Approach

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***Abstract*—Indian companies are yet to leverage the supply chain for competitive advantage and as such there are no initiatives to measure the performance of their existing supply chain systems. However, many multi-nationals dealing in FMCG are fully exploiting the benefits and are also moving towards web-enabled supply chains. In view of globalization and liberalization of the economy, Indian companies are being forced to change their ways of doing business to meet the competitive pressure. In the recent past, many progressive companies are re-engineering their business processes to challenge the ever-increasing competitive pressures in the market place. In this context, Supply Chain Management initiatives could be a competitive tool and measuring the performances against industry standards would go a long way in achieving International standards. However the existing performance measurement methods fail to provide significant assistance in supply chain development. The objective of this paper is to propose an innovative cross-boundary performance measurement method from a system perspective. Fuzzy set theory is introduced to address the real situation in the judgment and evaluation processes. This practice will definitely help in improving the supply chain performance.**

***Index Terms*-Cross-boundary approach, Weighted average aggregation method, Fuzzy set theory, Performance measurement systems (PMSs), Process based model, System perspective, Process and performance measurement hierarchy (PPMH), Performance measurement team (PMT).**

Subsets of U are
$\widetilde{A}, \widetilde{B}$

A	Row weight vector
A $_{N X M}$	Weight matrix of N elements by M evaluators
$f_{\widetilde{A}}(\mu)$	Degree of membership of element μ in $\widetilde{A}$
G	Finite universe of discourse of fuzzy Performance grade = (A, B, C, D, E, F)
p $_x$ (μ)	Degree of membership of value of μ in G
P	Performance grade matrix of each Performance measures by all evaluators
P$_{6XN}$	Performance grade matrix of NperformanceMeasures

Notations -

P$_G$ (μ), **P**	Performance grade set in **G**
$\widetilde{r}_{ij}$	Preference entry of pair wise comparison of element i over j, in the form of a triangular fuzzy number = (r_{ijl} r_{ijm} r_{iju})
$\widetilde{R}$	Judgment matrices with fuzzy entries of pair wise comparison by evaluators
T (l, m ,u)	Triple that denotes a triangular fuzzy number where l, m, u stand for the lower, moderate and upper values respectively of the support of the triangular fuzzy number
U	Universe of discourse
W^T	Weight vector of the M evaluator's opinions = ($w_1, w_2,\ldots\ldots,.w_M$)
α_{ij}	Discrete integers in [0, 2] that express the degree of fuzziness of the evaluators
$\widetilde{\alpha}_i$	Normalized importance weight of each element = (α_{il} α_{im} α_{iu})
δ_{ij}	Discrete integers in [-6, 6] that quantify the qualitative preference of element i over j
λ	Any real number in [0, 1]
μ	Element in **U**

I. INTRODUCTION

The Council of Logistics Management defines Supply Chain Management as "the process of planning, implementing and controlling efficient and cost effective flow of materials, in-process inventory, finished goods and related information from point-of-order to point-of-consumption, for the purpose of conforming to customer requirements". The fundamental objective of a high performance of supply chain is to produce products to match customers' demand cycle, while producing the greatest value possible to the customers. A number of technologies and managerial attention has gone into improving supply chain performance. The increasingly competitive environment calls for speedy, cost efficient, accurate and reliable supply chains. Supply chain

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management is no longer a matter of operational and functional areas of the firm. Today, it is a strategic issue demanding top-level management attention. The supply chain can have huge leverage on the creation of customer value. Supply chains will fight the new battle for market dominance; as such measurements around the supply chain are critical. If we look at competition today, it is supply chain versus supply chain. This brings out a situation that competitors might focus on developing superior supply chain Performance. Accordingly, companies will have to find or develop metrics to measure performance of supply chain.

Over the last decade of evolution of SCM, a steady stream of articles dealing with the theory and practice of SCM has been published, but the topic of performance measurement does not receive adequate attention. As an indispensable management tool, performance measurement provides necessary assistance for performance improvement in pursuit of supply chain excellence. However many critical drawbacks present in the existing performance measurement systems prevent it’s significant contribution to the development and improvement of SCM. In this paper an effective Holistic performance measurement approach is proposed.

II. REVIEW OF THE PERFORMANCEMEASUREMENT IN SCM

Performance measurement is defined as the process of quantifying effectiveness and efficiency of action into readable symbols to report [1], [2]. Today’s performance measurement assumes a far more significant role than quantification and accounting. Performance measurement can provide important feedback information to enable managers to monitor performances, to reveal progress, to enhance motivation and communication and diagnose problems [3], [4]. It also provides insight to reveal the effectiveness of supply chain strategies and to identify the success and potential opportunities. It makes indispensable contribution to decision making in SCM, particularly in redesigning the business goals and strategies and reengineering processes. There is very little literature available, dealing with system design and measures selection [5]. Performance measurement authority examined best-in-class industry performance of customer-facing and internal-facing measures in supply-chain management. Customer-facing measures, such as production flexibility and delivery performance, quantify how well a supply chain delivers products to the customer. Internal-facing measures, such as total supply-chain costs and cash-to-cash quantify how effectively an organization uses resources in creating value for the customer. The Metrics can also be classified as 1) Non-financial e.g. Cycle time, Customer Service Level, Inventory Levels, Resource utilization 2) Financial e.g. Cost of raw material, Revenue from goods sold, Activity-based costs such as Material handling, Manufacturing, Assembling, Inventory holding costs, Transportation costs etc. Traditional PMSs that are financially focusssed have already received wide criticism on short term and profit orientation, encouraging local optimization failing to support continuous improvement and one dimensional measures [6], [7], [8] . Also some major drawbacks of existing PMSs [6], [9], [10] are1) not in line with strategies 2) no balanced integration of financial and non-financial measures 3) absence of holistic perspective 4) local approach leading to local optima and lack of global approach and hence global optima. Given the cross-functional nature of many supply improvements, the system perspective is lacking in the existing PMSs.

III. THE PROPOSED APPROACH

This proposed innovative approach is very well explained here with the help of real field data of an existing Supply Chain of an industry from an automobile sector for which the project of rejuvenation is undertaken. A supply chain should be viewed as an integrated entity, and all the members should be functionally coordinated as an extended enterprise [6], [11]. The supply chain performances should be measured beyond the organizational boundaries rather than focusing locally [9]. Today's marketplace is shifting from individual company performance to supply chain performance: the entire chain's ability to meet end-customer needs through product availability and responsive, on-time delivery. Supply chain performance crosses both functional lines and company boundaries. To achieve the goal, you need performance measures, or "metrics", for global supply chain performance improvements. Therefore it is proposed to develop a simplified model to analyze the practical supply chains when measuring the performance.

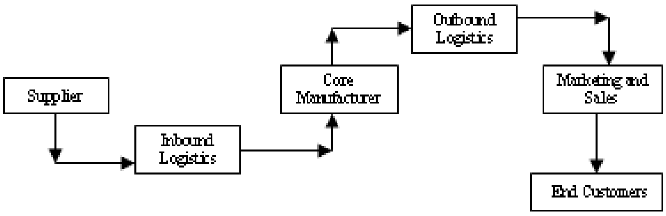

Figure 1: Information and Material Management

Six core processes are linked. These six processes are called key Processes. These key processes can be further decomposed into sub processes and activities to address their detailed performances. These processes form a hierarchy of supply chain model, which is the framework of the proposed PMS. The process based model enables the PMS to locate the problems easily and facilitates process re-engineering. This cross boundary system perspective and process based method span the whole supply chain, but rather blurs the organization and boundaries of the involved firms and departments. The performances should cover the areas like 1) those of critical concern to supply chain common goals and strategies 2) those of inter influence and of common concern among the supply chain partners and 3) those concerned with both internal partners and external customers. The existing performance measures are criticized as too many and too isolated. Here identification of multiple dimensions is achieved. Any process assumes particular functions at the cost of particular resources, and it pursues the planned goals in it’s particular inputs and outputs. Input dimensions are time and costs. Tangible outputs include semi finished products and finished products. There are a variety of intangible added values or outputs. These can be measured by assessing their functional performances with their missions. Then there are some composite measures such as productivity, efficiency and utilization which are widely used to assess the outputs in comparison with the inputs or expectation. All the composite measures should be well defined and normalized before their use. The methodology measures the performance of key supply chain processes. The proposed methodology facilitates deeper insight of the process performance from inputs and outputs aspect than the financial accounting method does. These operational dimensions of the process performance provide more visual information about the managerial effectiveness. For each process and sub process, the corresponding performance measures are identified respectively. Then the associated measures are respectively grouped into the hierarchy of the processes, thus building a process and performance measures hierarchy (PPMH). The PPMH for the Industrial supply chain under study is shown in Figure2. The priorities of various dimensions of performances should differ from each other due to changing strategies and goals. Accordingly it is necessary to set relatively different weights for each measure when aggregating the global measurement results of the holistic performances. Similarly individual decomposed processes are assigned relative weights to denote their various priorities when their measurement results are aggregated.

It is a challenging task beyond any individual to assess the comprehensive performances of the whole supply chain. In order to obtain the objective assessment of the holistic performances, channel- spanning participation of performance measurement activity is required. In this project, a performance measurement team (PMT) is suggested. The PMT is composed of the representatives from the various management areas of supply chain members. These representatives can be shop floor operators, process supervisors, department managers, plant managers etc. Members of the PMT serve mainly as the evaluators and provide a variety of opinions based on the measurement activity. The team members have wide backgrounds and experiences therefore represent wide range of views. When incorporating their opinions, the relative weights of the evaluators opinions must be assigned.

IV. THE NEW MEASUREMENT ALGORITHM

Once the measurement results of each performance measure have been obtained, a Weighted Average Aggregation method is used to incorporate the performance of the whole process. Similarly, the measurement results of all the sub processes can be aggregated into the result of their parent process. With this Aggregation method, the performance of each process on each level can be assessed.

a) Method to Assign Relative Weights to Performance Measures and Processes

The measures of every process or sub process must be weighted in order to address the changing objectives of the supply chains. The traditional pair wise comparison method by Saaty [12], called as Analytical Hierarchy Process (AHP), has some drawbacks. 1) It creates a very unbalanced scale of weight comparisons. Although this scale is presumably most widely used in practice, it's unbalanced disadvantage yields an unequal distribution of comparison ratios [13]. 2) Since the method uses discrete nos. for judgments, it eliminates the uncertainty associated with the mapping of the human perception and judgment to a number. There are naturally essential fuzziness and ambiguity in human judgments. The traditional comparison ratio scale with the crisp nos. as proposed in Saaty's AHP fails to address the fuzziness [14]. Therefore a geometric scale of triangular fuzzy numbers [15] is employed in this study to quantify the comparison ratios. Let U be the universe of discourse

$$\mathbf{U} = (\mu_1, \mu_2, \mu_3, \ldots\ldots\ldots\ldots, \mu_n).$$

A fuzzy number $\widetilde{A}$ is a fuzzy subset in the universe of discourse, **U** that is both convex and normal. The fuzzy number $\widetilde{A}$ has the meaning 'about A'. It is the natural generalization of a real crisp number, thus allowing formal representation for inexact concepts, subjective judgment and all types of evaluation. Among various membership functions, the triangular fuzzy no. is the most popular function employed in the engineering applications. The curve of the membership function is presented in Figure 3. According to Zadeh [16], a fuzzy set $\widetilde{A}$ of **U** is a set of ordered pairs $\{ (\mu_1, f_{\widetilde{A}}(\mu_1)), (\mu_2, f_{\widetilde{A}}(\mu_2)) ,\ldots\ldots\ldots\ldots (\mu_n, f_{\widetilde{A}}(\mu_n)) \}$, where $f_{\widetilde{A}} : \mathbf{U} \longrightarrow [0,1]$ is the membership function of $\widetilde{A}$, and $f_{\widetilde{A}}(\mu_i)$ represents the degree of membership of μ_i in $\widetilde{A}$.

$$\widetilde{A} = T(l, m, u) \quad (1)$$

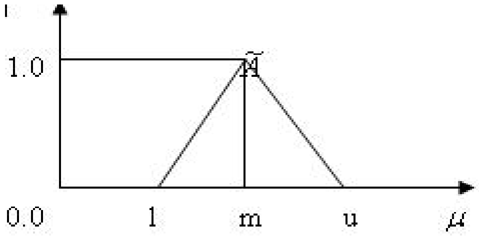

Figure 3: A Triangular Fuzzy Number

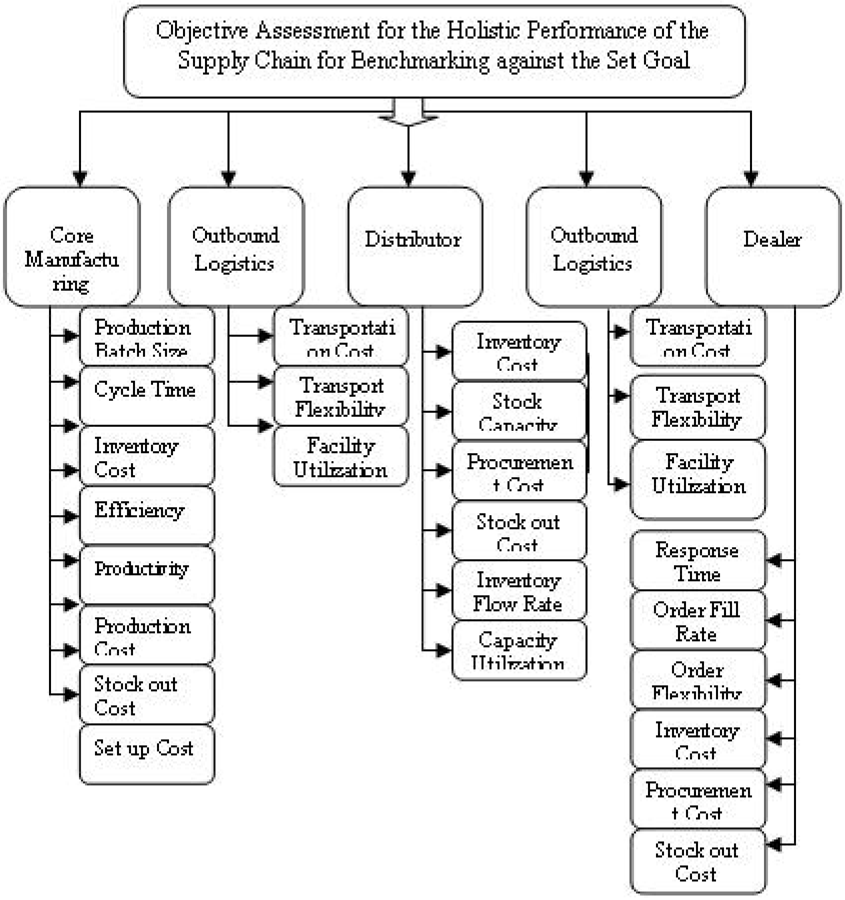

Figure 2: Process and Performance Measurement Hierarchy for the Supply Chain under Study

The geometric scale, whose echelons exhibit a discrete geometric progression, takes the following form of a triangular fuzzy number with exponential functions:

$$r_{ijl} = \exp[0.5(\delta_{ij} - \alpha_{ij})]$$

$$r_{ijm} = \exp[0.5(\delta_{ij})]$$

$$r_{iju} = \exp[0.5(\delta_{ij} + \alpha_{ij})] \quad (2)$$

where δ_{ij} quantify the qualitative preference ratios: parameter δ_{ij} help the evaluators to quantify their preference and judgments. The other integers between these defined values can be used to represent the moderate opinion between their meanings respectively. The parameter α_{ij} express the degree of fuzziness. The evaluators can respectively select the suitable fuzziness for their judgment. As a simple model for the judgment statements, all α_{ij} are denoted with a value α, where

$\alpha = 0$: no fuzziness
$\alpha = 1$: moderate fuzziness
$\alpha = 2$: significant fuzziness

Assume that there are N measures of a process to be weighted .i.e. i ,j = 1, 2,…….,N . Each evaluator is asked to provide his judgment concerning each pair of the measures

$\delta_{ij} = 0$: no preference of i over j
$\delta_{ij} = 2$: weak preference of i over j
$\delta_{ij} = 4$: strong preference of i over j
$\delta_{ij} = 6$: very strong preference of i over j

Similarly - δ_{ij} denotes some preference of j over i.

These discrete integers ranging from -6 to +6 of the (i, j), for i < j , in the form of fuzzy numbers $\tilde{r}_{ij} = T(r_{ijl}, r_{ijm}, r_{iju})$. As a consequence, via pair wise comparison by the evaluators, N x N judgment matrices with fuzzy entries will be obtained as follows. Here $\tilde{r}_{ji} = (1/\tilde{r}_{ij})$ and $\tilde{r}_{ii} = (1, 1, 1)$.

$$\tilde{R} = \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12}\cdots\cdots & \tilde{r}_{1N} \\ \tilde{r}_{21} & \tilde{r}_{22}\cdots\cdots & \tilde{r}_{2N} \\ \tilde{r}_{N1} & \tilde{r}_{N2}\cdots\cdots & \tilde{r}_{NN} \end{bmatrix} \quad (3)$$

According to the method of Buckley, the normalized importance weight of each measure will be derived as follows:

$$\tilde{\alpha}_i = (\alpha_{il}\ \alpha_{im}\ \alpha_{iu}) =$$

$$\left(\frac{\prod_{j=1}^{N} (r_{ijl})^{1/N}}{\sum_{i=1}^{N} \prod_{j=1}^{N} (r_{iju})^{1/N}}, \frac{\prod_{j=1}^{N} (r_{ijm})^{1/N}}{\sum_{i=1}^{N} \prod_{j=1}^{N} (r_{ijm})^{1/N}}, \frac{\prod_{j=1}^{N} (r_{iju})^{1/N}}{\sum_{i=1}^{N} \prod_{j=1}^{N} (r_{ijl})^{1/N}} \right. \quad (4)$$

As a result, the relative importance weights of the N measures of this process can be written in a row weight vector as follows:

$$\mathbf{A}^{\mathbf{T}} = (\tilde{a}_1, \tilde{a}_2, ...\tilde{a}_N) \quad (5)$$

When implementing this, the evaluators need to provide only the ordered pair of parameters (δ_{ij} , α_{ij}) to denote each pair wise comparison between the ith and jth measures.

b) Measurement Scale and Fuzzy Performance Grade

It is meaningless to assess any performance without it's associated context of objective and history [17]. Existing PMSs obtain this parameter just by dividing the current performance by the expectation. So existing systems have pitfalls like ignoring associated operation context and losing important information arising from the uncertainty of human judgments. Therefore a measurement algorithm based on fuzzy set theory is proposed here. Measurement scale is originally determined by the evaluators. When assessing the performance, the evaluators consider it's performance goal and history as well as associated operation environments, and then set the measurement scale in the form of an interval [bottom, perfect]. By the nature of human reasoning, the measurement scales are calibrated by dividing the interval proportionately. Similarly, the judgments of measurement scales contains much fuzziness and imprecision. Therefore the measurement results that are obtained through comparing current performances against their corresponding measurement scales are fuzzy too. In this project, this situation is taken care of by denoting the measurement results by triangular fuzzy numbers. Compared with the measurement scales, the current performances are denoted by performance scores ranging from 0 to 10, which correspond proportionally to the measurement scale intervals. The number 0 denotes the worst performance and number 10 denotes the perfect performance. A fuzzy performance grade set is defined as the fuzzy measurement result, which is denoted by a fuzzy vector **G** = {A, B, C, D, E, F}.

Assume that there are M evaluators in the PMT who assess one process with N performance measures. The weights for evaluators , W$_K$ (K= 1,2,…….,M) are denoted by the weight vector W^T = ($w_1, w_2, ..., w_M$) where $w_1 + w_2 + ... + w_M = 1$. As proposed above in equation (5), the relative weights of the N measures of this process can be written in a row weight vector by the K th evaluator as follows.

$$A_K{}^T = (\tilde{a}_{1K}, \tilde{a}_{2K}, ...\tilde{a}_{NK}) \quad (10)$$

All the weight vectors of N elements in a particular branch, by all the evaluators of the PMT, comprise the following N x M weight matrix A$_{NXM}$:

$$A_{NXM} = [A_1, A_2, A_3, ..., A_M]$$

These six grades A, B, C, D, E, F denote the gradational measurement results ranging from the perfect to the worst. All these grades are defined by the triangular fuzzy numbers of performance scores as shown in Figure 4.

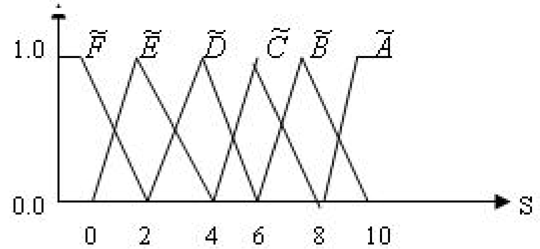

Figure 4: Triangular Fuzzy Grades

$$\tilde{A} = \text{T}\,(8, 10, 10), \quad \tilde{B} = \text{T}\,(6, 8, 10)$$
$$\tilde{C} = \text{T}\,(4, 6, 8), \quad \tilde{D} = \text{T}\,(2, 4, 6)$$
$$\tilde{E} = \text{T}\,(0, 2, 4) \quad \tilde{F} = \text{T}\,(0, 0, 2) \quad (6)$$

This performance grade set **P** in the finite universe of discourse, **G** = {A, B, C, D, E, F} is defined by a set of ordered pairs as follows.

$$P_G(\mu) = \{p_X(\mu), \mu), X = A, B, ..., F\} \quad (7)$$

where $p_x(\mu) : G \longrightarrow [0,1]$ is a mapping called the membership function of the fuzzy set **G,** and $p_x(\mu)$ indicates the degree of belongingness or membership value of μ in **G.**

$P_G(\mu)$ can be written in the form of sum as follows

$$P_G(\mu) = \frac{p_A(\mu)}{A} + \frac{p_B(\mu)}{B} + \frac{p_C(\mu)}{C} + \frac{p_D(\mu)}{D} + \frac{p_E(\mu)}{E} + \frac{p_F(\mu)}{F} \quad (8)$$

or

$$P_G(\mu) = \sum_{X \in G} \frac{p_X(\mu)}{X} \quad (9)$$

Physically, this gradation represents the quantification of the degree to which a particular performance satisfies the performance criteria set by the evaluators.

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c) Aggregating the Measurement Results

The resulting matrix is as shown below.

$$= \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} .... & \tilde{a}_{1M} \\ \tilde{a}_{21} & \tilde{a}_{22} .... & \tilde{a}_{2M} \\ \tilde{a}_{N1} & \tilde{a}_{N2} ...... & \tilde{a}_{NM} \end{bmatrix} \quad (11)$$

Thus the group opinion on the weights of the measures will be aggregated by a multiplying algorithm as follows.

$$A = A_{NXM}.W$$

$$= \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} .... & \tilde{a}_{1M} \\ \tilde{a}_{21} & \tilde{a}_{22} .... & \tilde{a}_{2M} \\ \tilde{a}_{N1} & \tilde{a}_{N2} ...... & \tilde{a}_{NM} \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ w_2 \\ w_M \end{bmatrix}$$

members compose the fuzzy performance grade matrix as follows:

$$=\begin{bmatrix} \tilde{a}_{11}w_1 + & \tilde{a}_{12}w_2 + ... & +\tilde{a}_{1M}w_M \\ \tilde{a}_{21}w_1 + & \tilde{a}_{22}w_2 + ... & +\tilde{a}_{2M}w_M \\ \tilde{a}_{N1}w_1 + & \tilde{a}_{N2}w_2 + ... & +\tilde{a}_{NM}w_M \end{bmatrix}$$

$$P(\mu) = \begin{bmatrix} P_{A1}(\mu), & P_{A2}(\mu),......., & P_{AM}(\mu) \\ P_{B1}(\mu), & P_{B2}(\mu),......., & P_{BM}(\mu) \\ P_{F1}(\mu), & P_{F2}(\mu),........, & P_{FM}(\mu) \end{bmatrix} \tag{14}$$

Also, the group opinion on measurement results will be aggregated by the multiplying algorithm as follows:

$$\mathbf{P} = P(\mu).W$$

$$= \begin{bmatrix} P_{A1}(\mu), & P_{A2}(\mu),......., & P_{AM}(\mu) \\ P_{B1}(\mu), & P_{B2}(\mu),......., & P_{BM}(\mu) \\ P_{F1}(\mu), & P_{F2}(\mu),........, & P_{FM}(\mu) \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ w_2 \\ w_M \end{bmatrix}$$

$$= \left[P_A, \ P_B, ..., \ P_F\right]^T \tag{15}$$

$$=\left[\tilde{a}_1, \ \tilde{a}_2,..... \ \tilde{a}_N\right]^T \tag{12}$$

Similarly, the performance grade by the K^th^ (K =1,2,……M) evaluator can be written in the forms of the row vector

$$P_K^T(\mu) = (p_{AK}(\mu), p_{BK}(\mu), p_{CK}(\mu), p_{DK}(\mu),$$
$$p_{EK}(\mu), p_{FK}(\mu))..(13)$$

For each performance, all the performance grade vectors of measurement results given by the PMT compose the performance grade matrix and then are aggregated with weighted average method again as follows:

$$= \begin{bmatrix} p_{A1}, & p_{A2},......., & p_{AN} \\ p_{B1}, & p_{B2},......, & p_{BN} \\ p_{F1}, & p_{F2},......., & p_{FN} \end{bmatrix}$$

$$P = P_{6\times N} .A$$

$$= \begin{bmatrix} p_{A1}, & p_{A2},......., & p_{AN} \\ p_{B1}, & p_{B2},......, & p_{BN} \\ p_{F1}, & p_{F2},......., & p_{FN} \end{bmatrix} \cdot \begin{bmatrix} \tilde{a}_1 \\ \tilde{a}_2 \\ \tilde{a}_N \end{bmatrix}$$

$$= \left[\tilde{p}_A, \ \tilde{p}_B,......., \ \tilde{p}_F\right]^T \tag{18}$$

Obviously $\tilde{p}_A, \tilde{p}_B, ..., \tilde{p}_F$ in the vector P of equation (18) are in the form of triangular fuzzy numbers respectively, which means the individual function membership of the triangular fuzzy number is also fuzzy. The most prevalent and physically appealing of all the defuzzification methods, the centre of gravity (COG), is used. The algebraic expression of the COG is stated as follows:

The method is as illustrated below.

$$F_1(\tilde{A}) = \frac{\int_{\tilde{A}} \mu . f_{\tilde{A}}(\mu).d\mu}{\int_{\tilde{A}} f_{\tilde{A}}(\mu).d\mu} \tag{19}$$

This performance grade vector can also be written as the summary

$$P = \frac{p_A}{A} + \frac{p_B}{B} + \frac{p_C}{C} + \frac{p_D}{D} + \frac{p_E}{E} + \frac{p_F}{F} \tag{16}$$

All these performance grade vectors

$$P_i^T = (p_{Ai}, p_{Bi}, p_{Ci}, p_{Di}, p_{Ei}, p_{Fi})$$

(i= 1,2,3,…..,N)

$$P_{6xN} = \left[P_1, \ P_2,........., \ P_N\right]$$

$$= \begin{bmatrix} p_{A1}, & p_{A2},......., & p_{AN} \\ p_{B1}, & p_{B2},......, & p_{BN} \\ p_{F1}, & p_{F2},......., & p_{FN} \end{bmatrix} \tag{17}$$

The relevant formula is as given below. By using this formula, the fuzzy numbers, $\tilde{p}_A, \tilde{p}_B, ..., \tilde{p}_F$ in the vector P are transformed into crisp numeric values respectively:

$$P = \frac{p_A}{A} + \frac{p_B}{B} + \frac{p_C}{C} + \frac{p_D}{D} + \frac{p_E}{E} + \frac{p_F}{F} \tag{20}$$

Thus this vector has the same form as the results in equation (8). It is the aggregated measurement result of the holistic performances of this particular process by the PMT. With a similar algorithm, the measurement results of each process can be incorporated layer by layer in the PPMH. All these results can be defuzzified into the crisp value in order to provide benchmark for the managers.

d) Defuzzifying the Measurement Results and Benchmarking

The fuzzy grades $A, B, ..., F$ are used to denote the notional values of measurement results.. The defuzzified result is defined as the performance index (PI), by the following formula:

$$PI = \frac{10\times p_A + 8\times p_B + 6\times p_C + 4\times p_D + 2\times p_E + 0\times p_F}{p_A + p_B + p_C + p_D + p_E + p_F} \tag{21}$$

Physically, the PI indicates the synthetic assessment of the holistic performances of the supply chain by the evaluator group. It reveals how a business process performs with respect to the planned goals and histories [18]. This simple number provides a concise means for analyzing and benchmarking the performances in the supply chain systems for their managers. Put in the full range [0, 10], this result can be benchmarked. Because the measurement results of each process on the higher layer is aggregated from the measurement results of sub processes, the worst result can be tracked layer by layer in the PPMH. Thus the strengths and weaknesses of supply chain process can be identified and located. Moreover the parallel processes can be compared and the problematic nodes can be discovered.

V. VALIDATION BY USING REAL FIELDDATA

By using this methodology, the performance index of an existing supply chain of an industry from an automobile sector for which the project of rejuvenation is undertaken, is calculated as follows.

The whole supply chain consisting of manufacturer, distributor and dealer along with inter-node logistics (As shown in Figure 2) is visualized as a single integrated process. There are three measures identified to indicate the three dimensions of it's performances: Total supply chain Cost, Service factor, Reliability. Four members are selected from different functional areas, to act as the members of PMT viz. General Manager of the Manufacturing Plant, Head of the Distribution Centre, Process Supervisor from the distribution company, Salesman at the Dealer's shop. These four evaluator's opinions are assigned relative weights depending on their functional importance in the process as $W^T = (0.5, 0.25, 0.15, 0.10)$ respectively. Firstly one evaluator makes the judgment of the measure cost. The cost estimated from the performance history and present status is Rs.7, 07,000/- for an average inventory of 500 vehicles along the supply chain. Cost/unit is Rs.1400. While the optimization of supply chain for minimum total supply chain cost and maximum service level has yielded the cost value as Rs. 6,42,700/- for an average inventory of 500 vehicles along the supply chain. Cost /unit is therefore Rs.1200. Hence the first evaluator determines the measurement scale of cost as the interval [14, 12]. Similarly the service factor estimated from performance history and present status is 0.9. While the optimization procedure yields a value of 1.7 at the minimum total supply chain cost. So the measurement scale of service factor is [0.9, 1.7]. The reliabilities of the different sub processes as per the performance history and current status are given in Table I. While the reliability aimed at is 1.0. Therefore the measurement scale interval for this performance parameter will be [0.5, 1].The current performance on supply chain cost averages to Rs.13.69/unit then we calculate the performance score and performance grades as follows:

$$= \begin{bmatrix} 0 & 0 & 0 & 0.1 \\ 0 & 0 & 0 & 0.9 \\ 0 & 0 & 0.95 & 0 \\ 0 & 0.55 & 0.05 & 0 \\ 0.775 & 0.45 & 0 & 0 \\ 0.225 & 0 & 0 & 0 \end{bmatrix}$$

Then the measurement results of these four evaluators with their respective weights are aggregated by applying equation (15). In a mathematical sense, this vector denotes the aggregated opinion of the measurement of cost performance of the four evaluators. It takes the form of a fuzzy performance grade set.

$$P_1 = P(\mu_1).W = \begin{bmatrix} 0 & 0 & 0 & 0.1 \\ 0 & 0 & 0 & 0.9 \\ 0 & 0 & 0.95 & 0 \\ 0 & 0.55 & 0.05 & 0 \\ 0.775 & 0.45 & 0 & 0 \\ 0.225 & 0 & 0 & 0 \end{bmatrix} . \begin{bmatrix} 0.5 \\ 0.25 \\ 0.15 \\ 0.10 \end{bmatrix}$$

Table I: Reliability of the supply chain

Sub process	Reliability of sub process	Reliability of supply chain
Manufacturing Plant	0.95	Whole SC process reliability = (0.95 x 0.85 x 0.90 x 0.80 x 0.85) = 0.49419 = 0.50
Outbound Logistics I	0.85	
Distribution Centre	0.90	
Outbound Logistics II	0.80	
Dealer	0.85	

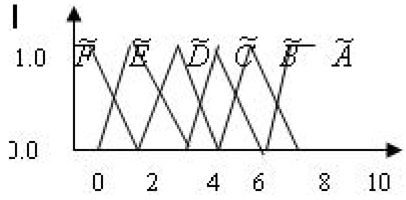


Figure 5: Performance Score to Performance Grade

Performance score is

$$\frac{14-13.69}{14-12} \times (10-0) = 1.55$$

Thus the performance grade set can be written as follows:

$$P_1^T(\mu_1) = (0,0,0,0,0.775,0.225)$$

This is the measurement result of total supply chain cost judged by the first evaluator. The performance grade sets of the other three evaluators calculated in a similar way are given below. The performance grade sets of the other three evaluators calculated in a similar way are

$$P_2^T(\mu_1) = (0,0,0,0.55,0.45,0)$$

$$P_3^T(\mu_1) = (0,0,0.95,0.05,0,0)$$

$$P_4^T(\mu_1) = (0.1,0.9,0,0,0,0)$$

These four vectors compose the fuzzy performance grade matrix with equation (14) as follows:

$$P(\mu_1) = [P_1(\mu_1), P_2(\mu_1), P_3(\mu_1), P_4(\mu_1)]$$

$$P_1 = [0.01, 0.09, 0.1425, 0.1450, 0.50, 0.1125]^T$$

The performance grades of the other two performances i.e. the service factor and reliability are calculated in a similar way, by the members of PMT and are given below:

$$P_2 = [0.2188, 0.3125, 0.2188, 0.0375, 0.1750, 0.0375]^T$$

$$P_3 = [0.0.0, 0.4, 0.2250, 0.2300, 0.1350, 0.0100]^T$$

For all these three performance measures, the performance grade vectors of this process compose the 6 x 3 performance grade matrix of the process with equation (17) as follows:

$$P_{6\times 3} = [P_1, P_2, P_3]$$

$$= \begin{bmatrix} 0.01 & 0.2188 & 0 \\ 0.09 & 0.3125 & 0.4 \\ 0.1425 & 0.2188 & 0.2250 \\ 0.1450 & 0.0375 & 0.2300 \\ 0.50 & 0.1750 & 0.1350 \\ 0.1125 & 0.0375 & 0.0100 \end{bmatrix}$$

After the performance grade matrix and the local relative weights of the three performances of this process have been obtained, the measurement result of this process can be aggregated by applying equation (18) as follows:

A_1^T = ((0.116031, 0.348212, 1.0000), (0.025893, 0.077708, 0.231627), (0.161932, 0.574079, 1.0000))

A_2^T = ((0.06798, 0.22728, 0.75616), (0.01517, 0.04293, 0.120915), (0.25787, 0.72978, 1.0000))

A_3^T = ((0.166147,0.438383,1.0000), (0.085308, 0.190527, 0.423730), (0.140642, 0.371089, 0.974923))

A_4^T = ((0.0530987, 0.153564, 0.441341), (0.1034139, 0.3533312, 1.0000), (0.170491, 0.493103, 1.0000))

These four vectors compose the 3 x 4 weight matrix using equation (11):

$$A_{3\times4} = [A_1, A_2, A_3, A_4]$$

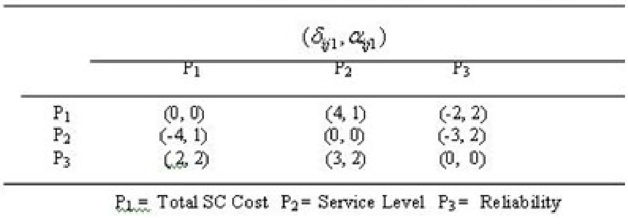
With the relative weights of the evaluator's opinions, in the judgments of the performance local weights are incorporated by applying equation (12):

$$A = A_{3\times4}.W$$

$$= \begin{matrix}[(0.1052,0.3120,0.8832),\\ (0.0399,0.1135,0.3096),\\ (0.1836,0.5745,0.9962)]^T\end{matrix}$$

The next step is to derive the local relative weights of the three measures. According to the method described in section 4, the four evaluators respectively provide the ordered pairs for the three measures. For e.g. Tables II illustrates the judgments of the first evaluator. The four weight vectors of the three measures respectively by the four evaluators are obtained according to the calculation algorithm in equations (3) to (5):

Table II: The Pair Wise Comparison by Evaluator 1



	$(\delta_{ij1}, \alpha_{ij1})$		
	P1	P2	P3
P1	(0, 0)	(4, 1)	(-2, 2)
P2	(-4, 1)	(0, 0)	(-3, 2)
P3	(2, 2)	(3, 2)	(0, 0)

P1 = Total SC Cost P2 = Service Level P3 = Reliability

$$P = P_{6\times3}.A$$

$$= \begin{bmatrix} 0.01 & 0.2188 & 0 \\ 0.09 & 0.3125 & 0.4 \\ 0.1425 & 0.2188 & 0.2250 \\ 0.1450 & 0.0375 & 0.2300 \\ 0.50 & 0.1750 & 0.1350 \\ 0.1125 & 0.0375 & 0.0100 \end{bmatrix} . \begin{bmatrix} 0.1052 & 0.3120 & 0.8832 \\ 0.0399 & 0.1135 & 0.3096 \\ 0.1836 & 0.5745 & 0.9962 \end{bmatrix}$$

$$= \begin{bmatrix} 0.0098 & 0.0280 & 0.0766 \\ 0.0954 & 0.2933 & 0.5747 \\ 0.0650 & 0.1986 & 0.4177 \\ 0.0590 & 0.1816 & 0.3688 \\ 0.0844 & 0.2534 & 0.6303 \\ 0.0152 & 0.0451 & 0.1209 \end{bmatrix}$$

This result can be defuzzified into the crisp value to be benchmarked by applying equations (19) and (20):

$$P = \frac{0.03813}{A} + \frac{0.32113}{B} + \frac{0.2271}{C} + \frac{0.20313}{D} +$$
$$\frac{0.3227}{E} + \frac{0.0604}{F}$$
$$PI = 4.921464$$

This number reveals how the process performs with respect to the planned goals and histories. The global PI presents clear measurement results in the form of brief numerical score for supply chain managers.

VI. CONCLUSION

A process based model, appropriate performance measures, teamwork evaluation and fuzzy measurement algorithm are used to measure and improve the performance of supply chain under analysis by using cross-boundary measurement method from a system perspective. The introduction of fuzzy set theory in setting weights and measuring performances is advantageous, because this fuzzy method addresses the real situation of human judgment with fuzziness in measurement activity without losing important information as the crisp method does. The concise defuzzified results provide easy assess for benchmarking the performances and avoiding excessive proliferation of data. With this data, the supply chain managers can easily benchmark the performance of the whole system and can analyse the effectiveness of their strategies leading to identification of the potential opportunities.

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