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ORIGINAL ARTICLE

Manufacturing system's effectiveness measurement by using combined approach of ANP and GTMA

Sanjeev Goyal · Sandeep Grover

Abstract Evaluating effectiveness of a manufacturing system is increasingly recognized as a tool for gaining competitive success. Today, lot of new manufacturing technologies are coming into the market. To build confidence of managers in adopting these new technologies, measurement of their effectiveness is must. So, developing a model on measurement of effectiveness for a manufacturing system will be significant from strategic management point of view. Manufacturing effectiveness factors from the literature and an expert questionnaire were utilized prior to building the effectiveness measurement model. To prioritize these, we used well known multi-attribute decision making (MADM) technique-Analytical Network Process (ANP). ANP allows interdependencies and feedback within and between clusters of factors. ANP is the generalized form of AHP. A group of experts were consulted to establish interrelations and to provide weightage for pairwise comparison. Outcome of the ANP is weighted comparison of the factors. A Manufacturing System Effectiveness Index (MSEI) is also calculated by using robust MADM technique-Graph Theoretic and Matrix Approach (GTMA). This index is a single numerical value and will help managers to benchmark the effectiveness of manufacturing system with their peers. A case study in three organisations is performed to demonstrate and validate the use of GTMA for calculation of MSEI. To the authors' knowledge, this will be the first study which used combine approach of ANP and GTMA leading to single numerical index of effectiveness for a manufacturing system.

Keywords: Effectiveness of manufacturing system · Critical factors · Analytical Network Process (ANP) · Graph Theory and Matrix Approach (GTMA) · Multi-attribute decision making (MADM)

1 Introduction

Globalization has put manufacturers into fierce competition. Customer is enjoying variety of products with lesser price. Traditional manufacturing methods are not sufficient for survival in this ever closing world. In the recent times, manufacturers have adopted many modern methods and techniques to improve the effectiveness of their manufacturing systems such as advanced manufacturing technologies, TQM, JIT, lean manufacturing and many more. These newer technologies although provide great deal of advantages at every operation, yet industries have failed to yield the anticipated benefits completely. The reason for this is due to complex nature of these technologies which depend upon many critical factors. Moreover, industries fail to develop proper strategies to realize their actual business needs resulting into adoption of inappropriate investments in these technologies. Due to advances in metrology, mechanistic or physical measurements could be made extremely accurately, still, the measurement of manufacturing effectiveness remains an unsettled issue due to its complex and multi-dimensional nature (Hon 2005). In fact, strategies should be combined with appropriate measurement methods with financial and non-financial information,

S. Goyal (✉) · S. Grover
Department of Mechanical Engineering, YMCA University of Science & Technology, Faridabad, Haryana, India
e-mail: goyal.sanjeev@hotmail.com

S. Grover
e-mail: groversandeep@hotmail.com

which will be helpful in measuring, monitoring and encouraging an output of strategy (Golec and Taskin 2007; Ghalayini et al. 1997; Wang et al. 2008; Yang et al. 2009).

Effectiveness is the ratio of actual output to the reference output. Hayes and Wheelwright (1984) developed a four stage model for measuring the effectiveness of a manufacturing system. As Wheelwright and Hayes (1985) suggested, “a given operation may be—and often is—composed of factors that are themselves at different levels of development. What determines the overall level of the operation is where the balance among these factors falls”. Therefore, to develop a model on effectiveness evaluation, first of all, the critical factors are to be identified. Selection of critical factors should be appropriate for manufacturers keeping in mind the company’s strategic intentions that suit competitive environments and the nature of business (Yang et al. 2009). The measurement model based on the chosen critical factors should be simple and help managers to realize their goals.

To achieve this, this study proposes a measurement model for evaluating the effectiveness of a manufacturing system and generates a Manufacturing System Effectiveness Index (MSEI) to assist manufacturing managers in realizing their goals with clear vision. In general, this model identifies the various critical factors and creates their inter dependence in multi-attribute decision analysis. The measurement model should be accurate, otherwise it may give wrong directions mislead the company into losses. To accurately, measure the effectiveness of a manufacturing system, this research paper proposes the combine use of Analytical Network Process (ANP) and Graph Theory and Matrix Approach (GTMA), the well-established approaches. ANP finds the importance of critical factors by evaluating their interdependence and generates weights for every factor. These weights are used in GTMA to find the MSEI. This index will be a single numerical number which will give the overall effectiveness of a manufacturing system. This research paper will help managers to benchmark their manufacturing system with the peers.

2 Literature review

In this section, we will briefly review the literature pertaining to the work in the field of effectiveness/performance measurement of manufacturing system, use of ANP and GTMA in multi-attribute decision making (MADM).

2.1 Evaluation of effectiveness for a manufacturing system

Measuring effectiveness of a manufacturing system is a challenging task because of its dependence on many critical factors, which further inter-depend upon each other (Kueng 2000). Most critical factors have a relationship, which is either conflicting or complementary; independence is the exception rather than the rule. The traditional measuring systems based on financial terms lack the advantage of incorporating intangible factors like flexibility, employee, quality etc. Moreover, these methods do not have the advantage of continuous monitoring and improvement of the system (Lee et al. 2007; Ghalayini et al. 1997; Wang et al. 2008).

The Measurement model should be simple, cognitive, objective and it should provide continuous improvement to the system. Leong et al. (1990) proposed a performance measurement model based on five factors: quality, delivery, cost, flexibility and innovativeness through literature survey. These factors were further decomposed into 37 subfactors. Ghalayini et al. (1997) provided an integrated dynamic performance measurement system that helps managers in identifying key areas that need improvement. This model has eight dimensions: customer satisfaction, integration with customers, quality, delivery, manufacturing cycle time, cost of non-value-added activities, process technology, and education and training. Tan and Platts (2004) developed a software tool based on AHP to analyse the inter-relationship between factors in hierarchical way. Hon (2005) evaluated the different manufacturing systems on the basis of five dimensions: productivity, quality, flexibility, cost and time. Golec and Taskin (2007) considered five main factors and 47 subfactors for evaluation of a manufacturing system through fuzzy AHP and SWF. The main limitation of this study is, not considering the interrelationship of the subfactors with each other, which is rather unusual. Yang et al. (2009) proposed an evaluation model for manufacturing system by using AHP/ANP and considered six main dimensions: cost, delivery, flexibility, utilization, employee and quality. These dimensions were further decomposed into 44 criteria. The main drawback in this paper is, it only considers interdependence in hierarchical way and not at the same level. Moreover, the choice of the subfactors seems to be repretive one. Jain et al. (2011) evaluated the manufacturing performance by using DEA. There are constraints for the application of the DEA in developing a performance evaluation model of a manufacturing system. First, it requires at least two alternatives for each input or output measure (Bowlin 1987). If the outputs are large then this may become a constraint. DEA often generates several attractive choices that all lie along the DEA frontier line, and it is difficult to choose among these on rational grounds. The inputs and outputs in the DEA approach should be somewhat related experientially, statistically and/or conceptually.

While these investigates have concentrated on either the selection of performance measures or particular relationships among key measures, authors did not find any literature that has attempted to realize the interrelationships among the factors at the same level and gives a single numerical index for evaluating the effectiveness of a manufacturing system objectively.

2.2 Analytic network process (ANP)

ANP is a general form of AHP. AHP was first proposed by Saaty (1980a, b). The AHP is a widely used MADM based on the representation of a decision making problem by a hierarchical structure where elements are independent and unidirectionally linked. By considering both qualitative and quantitative aspects of a decision and through a pairwise comparison, it allows to set priorities among the elements and make the best decision. Decision problems are not always structured in a hierarchal way i.e. they may have interrelations among the elements at the same level. To overcome this difficulty, ANP was introduced by Saaty (1996). ANP simultaneously takes into account both feedback and dependence. ANP generalizes the AHP by allowing networks with or without hierarchal structure. ANP makes the best decision by allowing feedback within elements of a cluster (inner dependence) or between clusters (outer dependence). ANP methodology is explained in Saaty's book (2005). A brief description is given here because of space limitation. The ANP comprises of four major steps:

Step 1 *Model construction through networks*. Decision problem should be structured into networks by using appropriate methods or through brainstorming.

Step 2 *Pairwise comparison and priority vectors*. Decision makers are asked to compare clusters through a series of questions for inner and outer dependence to achieve the goal. The relative importance values are determined on the scale of 1–9. Where a score of 1 represents the equal importance among the elements and a score of 9 represents the extreme importance of one element over the other (Meade and Sarkis 1999). A reciprocal value is assigned to the inverse comparison i.e. $b_{ij} = 1/b_{ji}$. Local priority vectors are derived similar to AHP. This step is done to derive the eigenvectors and to form a supermatrix.

Step 3 *Supermatrix formation*. The outcome of step 2 is unweighted supermatrix. Supermatrix is actually a partitioned matrix. Its columns represent priorities derived from the pairwise comparison of the elements. As unweighted supermatrix may not be column stochastic, so as to obtain one, multiply each block with cluster priority obtained in the step 2. This stochastic matrix is known as weighted supermatrix. To obtain a convergence on the importance of weights, the supermatrix is raised to large powers and the resulted matrix is known as limit matrix. Priorities can be directly obtained from the limit matrix.

Step 4 *Selection of alternatives*. The alternative with the largest priority should be selected.

There are multiple applications of ANP in many areas. Some representative ones are: product mix planning in semiconductor fabricator (Chung et al. 2005); modeling the metrics of lean, agile and leagile supply chain (Agrawal et al. 2006); manufacturing system evaluation in wafer industry (Yang et al. 2009); purchasing decisions (Ustun and Demirtas 2009); supplier selection (Lang et al. 2009); prioritizing success factors in manufacturing enterprises (Karpak and Topcu 2010); customer relationship management (Oztaysi et al. 2011).

2.3 Graph theory and matrix approach

Graph theoretic and matrix model consists of digraph representation, matrix representation and permanent representation. It is a powerful technique to calculate single numerical index for evaluation of critical factors pertaining to a problem of any field. Grover et al. (2004, 2006) has applied it for TQM evaluation of an industry and to find the role of human factors in TQM. There are multiple other applications of GTMA in many areas; some representative ones are: robot selection (Agrawal et al. 1991), failure cause analysis (Gandhi and Agrawal 1996), development of maintainability index for mechanical systems (Wani and Gandhi 1999), machinability evaluation of work materials (Rao and Gandhi 2002), capability envelop of a machining process (Huang and Yip-Hoi 2003), performance evaluation of TQM in Indian industries (Kulkarni 2005), selection, identification and comparison of industrial robots (Rao and Padmanabhan 2006), to optimize single-product flow-line configurations of RMS (Dou et al. 2009) and so on.

2.3.1 Main objectives of the graph theoretic approach

- It is a tool which is used to calculate the single numerical index of any issue.
- It converts the intangible issues into tangible i.e. it quantify the subjective issues.
- It helps to compare the different alternatives on the basis of the single numerical index.

2.3.2 Attribute digraph

As per Graph Theoretic Approach, First of all, a digraph is made to show the attributes and their interdependencies

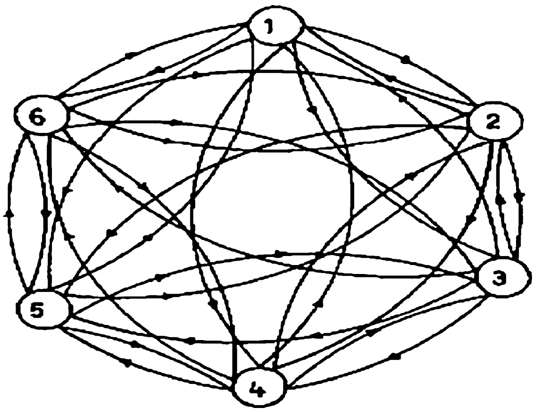


Fig. 1 Attribute digraph

within the system. A graph with directed edges is known as digraph. The nodes in the evaluation digraph represent the qualitative measure of the attributes (D_i's) and edges show the interdependencies of the attributes (D_{ij}'s). The digraph consists of a set of nodes $V = \{V_i\}$, with $i = 1, 2, 3,\ldots, M$ and a set of directed edges $D = \{D_{ij}\}$. A node V_i represents the ith qualitative attribute and the edges represents the relative importance among them. The number of nodes represents the total number of attributes considered for the evaluation. If a node 'i' shows the relative importance over node 'j', then a directed edge is drawn from node 'i' to node 'j' (i.e. D_{ij}). A typical digraph is shown in Fig. 1 with six attributes.

Similarly if node 'j' shows relative importance over node 'i' then a directed edge is drawn from node 'j' to node 'i' (i.e. D_{ji}).

2.3.3 Matrix representation of attribute digraph

The Digraph representation gives visual analysis. But if the factors are large, then it becomes too complex to understand. Moreover, for mathematical analysis, the digraph should be represented in the matrix form. The matrix represents all the attributes and their interrelations. Hence a matrix called evaluation attribute matrix is defined. Here in this matrix 'D_i' represents the ith evaluation attribute represented by the node 'V_i' and 'D_{ij}' represents the relative importance among the attributes and is represented by the edge drawn from i to j in the digraph.

$$A = \begin{array}{c} \text{Attributes} \\ 1 \\ 2 \\ 3 \\ - \\ - \\ N \end{array} \begin{array}{c} \begin{array}{cccccc} 1 & 2 & 3 & - & - & N \end{array} \\ \begin{bmatrix} D_1 & a_{12} & a_{13} & - & - & a_{1N} \\ a_{21} & D_2 & a_{23} & - & - & a_{2N} \\ a_{31} & a_{32} & D_3 & - & - & a_{3N} \\ - & - & - & - & - & - \\ - & - & - & - & - & - \\ a_{N1} & a_{N2} & a_{N3} & - & - & D_N \end{bmatrix} \end{array} \tag{1}$$

The determinant of this matrix will give important information regarding the evaluation of attributes. But it will contain negative terms so some useful information will be lost. To solve this problem, researchers have used permanent function of the matrix. The only difference between determinant and permanent function is in the signs of the coefficients. Where determinant has both negative and positive signs in the terms, there only positive signs appears in the permanent function, which ensures that complete objective for the evaluation of the attribute is fulfilled and no information is lost. Permanent is a standard matrix function and is used in combinatorial mathematics

$$\begin{aligned} \mathrm{per}A = {} & \prod_{i=1}^{6} D_i + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (a_{ij}a_{ji})D_kD_lD_mD_n + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (a_{ij}a_{jk}a_{ki} + a_{ik}a_{kj}a_{ji})D_lD_mD_n \\ & + \left[\left(\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (a_{ij}a_{ji})\,(a_{kl}a_{lk})D_mD_n + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (a_{ij}a_{jk}a_{kl}a_{li} + a_{il}a_{lk}a_{kj}a_{ji})D_mD_n\right)\right] \\ & + \Bigg[\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (a_{ij}a_{ji})\,(a_{kl}a_{lm}a_{mk} + a_{km}a_{ml}a_{lk})D_n \\ & + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (a_{ij}a_{jk}a_{kl}a_{lm}a_{mi} + a_{im}a_{ml}a_{lk}a_{kj}a_{ji})D_n\Bigg] \\ & + \Bigg[\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (a_{ij}a_{ji})\,(a_{kl}a_{lm}a_{mn}a_{nk} + a_{kn}a_{nm}a_{ml}a_{lk}) + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (a_{ij}a_{jk}a_{kl})\,(a_{lm}a_{mn}a_{nl}) \\ & + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (a_{ij}a_{ji})\,(a_{kl}a_{lk})\,(a_{mn}a_{nm}) + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (a_{ij}a_{jk}a_{lm}a_{mn}a_{ni} + a_{in}a_{nm}a_{ml}a_{lk}a_{kj}a_{ji})\Bigg] \end{aligned} \tag{2}$$

(Marcus and Minc 1965). The adjacency matrix, incidence matrix, characteristic matrix, etc. could be used, but they have their own drawbacks.

2.3.4 Permanent function of the attribute matrix

The permanent function of the attribute matrix is represented as Per (*A*). It contains N! terms. Equation 2 shows the sigma form of the permanent function for six attributes, if the attributes are more, than it can be further extended.

In this total $(n + 1)$ i.e. $(6 + 1)$ groupings have been made. These groups represent the measure of attributes and the relative importance. Here total seven groups have been made and their importance is discussed below.

1. The first grouping represents the measures of inheritance level of implementation factors.
2. The second grouping is absent as there is no self-loop in the digraph.
3. The third grouping contains interrelationships between the subfactors (i.e. $a_{ij}\,a_{ji}$) and measures of four remaining factors.
4. The fourth grouping represents a set of three factors relative importance loop and measure of three factors.
5. The fifth grouping contains two subgroups. The terms of the first subgroup represents the relative importance among the two factors and the measure of two implementation factors. The second subgroup contains the relative importance among the four factors and the measure of the two implementation factors.
6. The sixth grouping contains two subgroups. The first subgrouping is a set of two factor interdependence, i.e. $a_{ij}a_{ji}$, a set of three factor interdependence, i.e. $a_{kl}a_{lm}a_{mk}$ or its pair $a_{km}a_{ml}a_{lk}$ and measure of remaining implementation factor. The second subgrouping is a set of five implementation factors interdependence, i.e. $a_{ij}a_{jk}a_{kl}a_{lm}a_{mi}$ or its pair $a_{im}a_{ml}a_{lk}a_{kj}a_{ji}$ and measure of remaining implementation factor.
7. Similarly seventh grouping analyses sub-grouping in terms of a set of two and four behavioural factor interdependence, two to three behavioural factor interdependence, three to two behavioural factor interdependence and six implementation factors interdependence.

The permanent function of GTMA approach will be used to calculate MSEI. This index can be used to compare different alternatives or industries.

2.3.5 Effectiveness evaluation model of a manufacturing system

To build an effectiveness evaluation model, this study proposes the combined application of ANP and GTMA.

2.4 Application of ANP

Application of ANP is a four-step procedure: identifying the critical factors and subfactors, building networks of factors and subfactors, pairwise comparison, building supermatrices to find relative importance among the factors.

Step 1 *Identification of factors and subfactors*. Critical factors are identified as per the literature reviewed in Sect. 2. These factors are generalized into seven clusters with 65 subfactors. The seven clusters are: cost, delivery performance, employee, flexibility, productivity, quality and sustainability. Further experts from industries, academicians and research scholars were asked to select the most appropriate subfactors for evaluation. With their consultation, finally 35 subfactors are selected. This is shown in Fig. 2. The description of the factors and subfactors is given in Table 1.

Step 2 *Building networks of factors and subfactors*. After identifying the factors and subfactors, these experts established the interrelationship among them, which is shown in Table 2. These interrelationships provide the foundation for prioritizing factors when attempting to maximize the effectiveness of manufacturing system. Based upon inter-relations among subfactors, a network is formed, which forms the basis for applying ANP. The network is shown in Fig. 3.

Step 3 *Pairwise comparison and building supermatrices*. ANP Superdecisions 2.0.8 software has been used for the ANP computations. Based upon interdependencies established in the previous step, the group of experts evaluated the pairwise comparison on Saaty's scale (1996) by answering the questionnaire. One such questionnaire regarding the 'employee cluster' is given in Fig. 4. In this questionnaire, every subfactor of 'employee cluster' is evaluated on 1–9 point scale with each other. Here, 1 represent the equal importance, while 9 represent the high importance of one factor over the other. These comparison scores are then entered into the ANP model using the interface provided by the Superdecisions software. The consistencies of the data have been checked using the Superdecisions

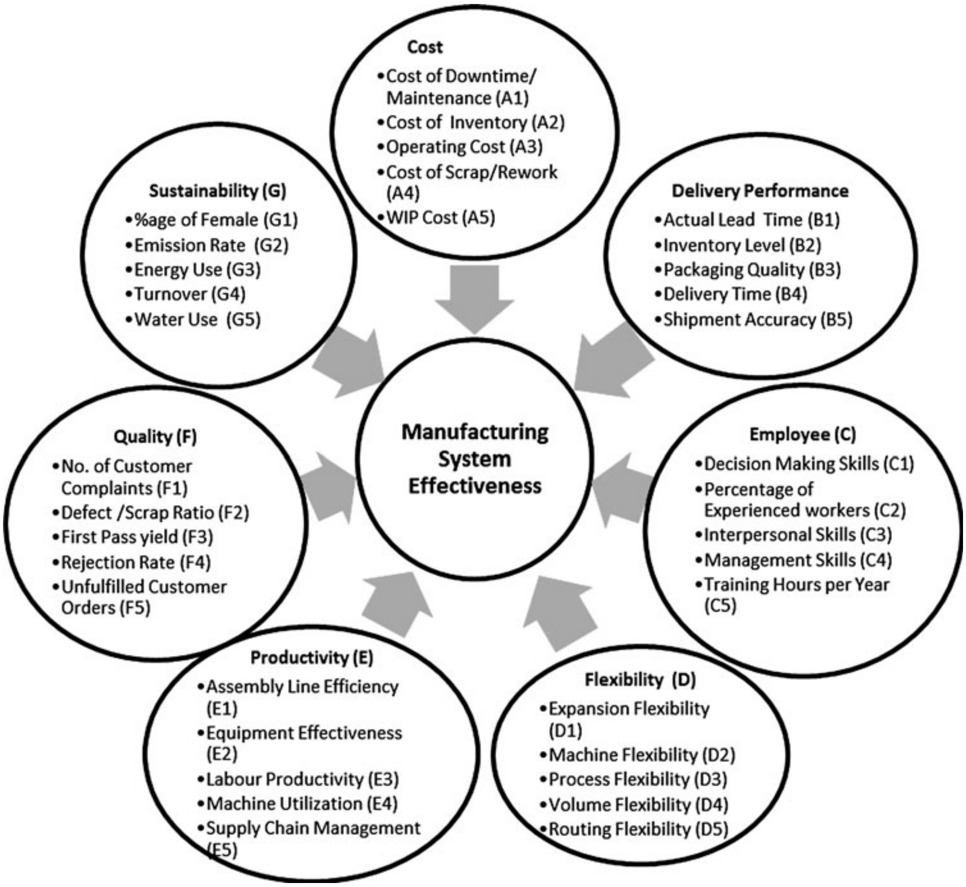


Fig. 2 Effectiveness evaluation clusters and detailed criteria

software. It was made sure that consistencies should lie below 0.1, but in some data these were up to 0.17, which is tolerable according to Saaty (2005). Finally, using the software package Superdecisions 2.0.8 unweighted, weighted, limit, priority, cluster matrix (as discussed in Sect. 2.2) are obtained and are shown in Tables 3, 4, 5, 6, 7.

Step 4 *Prioritization of factors*. As shown in Table 6, five most important criteria turns out to be Turnover (13.885 %), Supply Chain Management (6.7 %), First Pass Yield (5.8 %), Percentage of Experienced Workers (5.5 %) and Management Skills (4.8 %). Priority list along with rank of each criterion is given in Table 6.

2.5 Application of GTMA to calculate MSEI

To demonstrate and validate the calculation of MSEI, a case study has been conducted in three organisations A, B and C. These organisations are engaged in the manufacture of sheet metal components, having a turnover of US\$1.3 million, US\$0.7 million and US\$0.2 million and employing 750, 503 and 256 employees respectively. These companies manufacture 10–20 models of their products and change overtime of 20–90 min from one model to another has been reported. For this purpose, a questionnaire asking to rate 35 subfactors on the Likert scale with reference to organisation's performance was given at the top, middle and lower management levels. After analysing the responses through this questionnaire, some experts were approached and the results were shared for their opinions. These experts were at the level of Deputy General Manager and above. The averages of responses for the given subfactors are listed in the last three columns of Table 6.

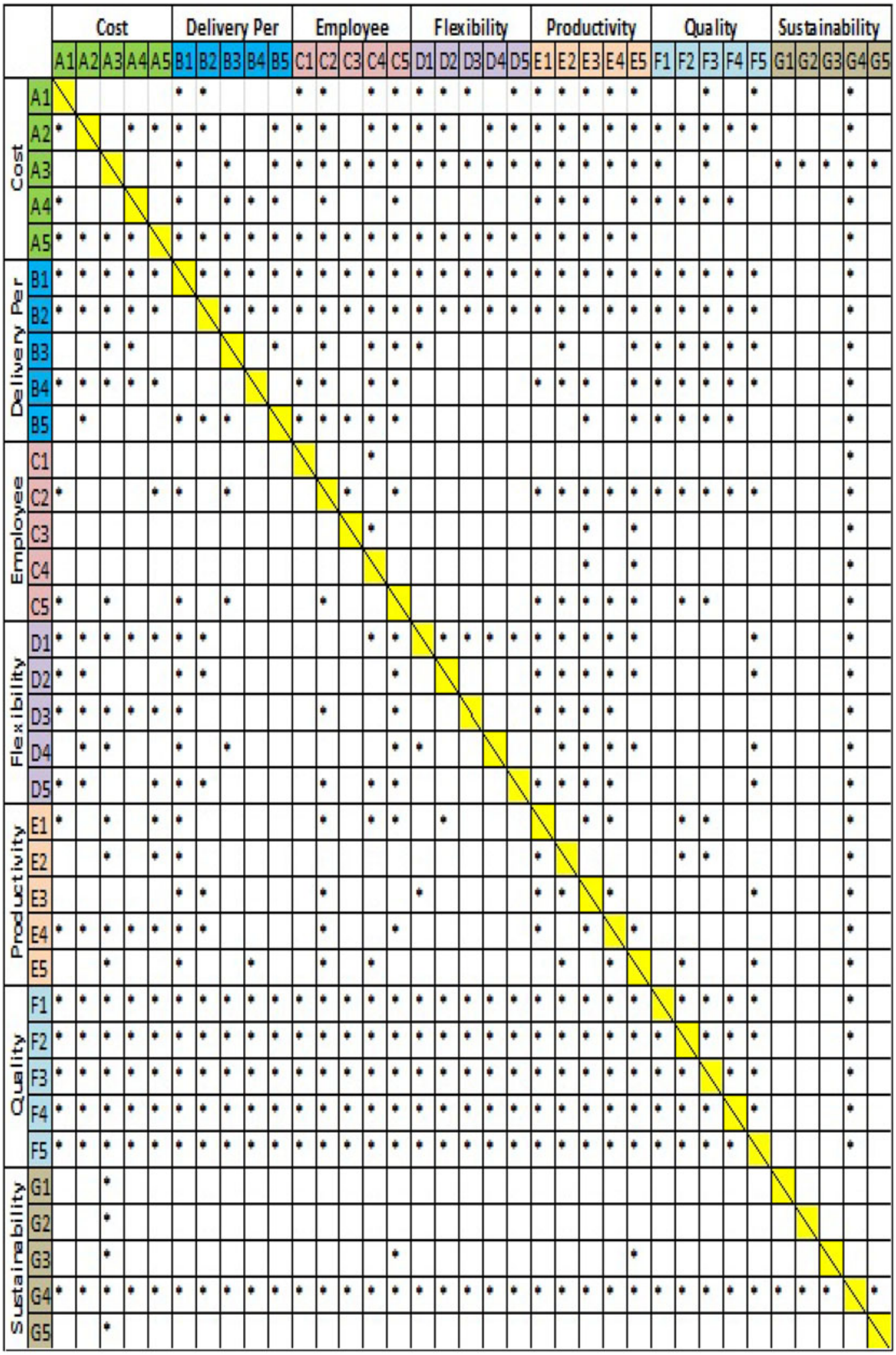
To calculate MSEI, GTMA is applied as discussed in Sect. 2.3. First of all digraph of each cluster is made, showing interrelations among subfactors.

$$A = \begin{array}{c} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{array} \begin{array}{c} \begin{array}{ccccc} E_1 & E_2 & E_3 & E_4 & E_5 \end{array} \\ \begin{bmatrix} 2.7 & 0.3 & 0.12 & 0.07 & 0 \\ 0 & 3.2 & 0.06 & 0 & 0.12 \\ 0.11 & 0 & 3.3 & 0.03 & 0 \\ 0.11 & 0 & 0.06 & 3.1 & 0.12 \\ 0 & 0 & 0 & 0.23 & 3.9 \end{bmatrix} \end{array} \quad (3)$$

Table 1 Description of effectiveness evaluation clusters and detailed criteria

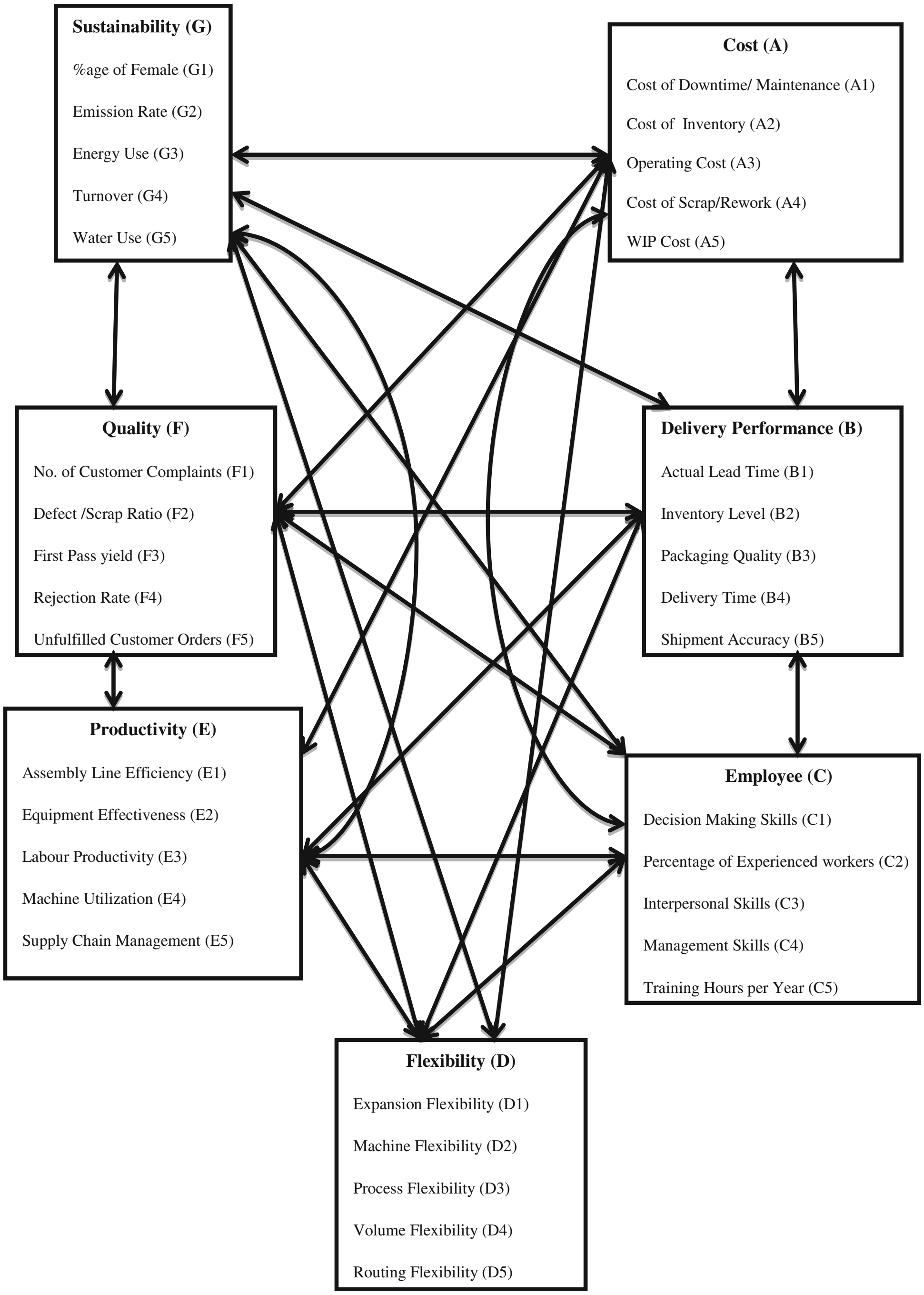
	Cluster and criterion	Description
1	Cost (A)	Cost or return on investment is a prime factor for evaluation
	A1 Cost of downtime/maintenance	Losses in the area of service, labour, machine time contribute to downtime
	A2 Cost of inventory	The cost of holding goods in stock
	A3 Operating cost	Cost per unit of a product or service
	A4 Cost of scrap/rework	Cost incurring due to wastage or rework
	A5 WIP cost	Cost of partially completed parts
2	Delivery performance (B)	It is a tool to measure the fulfilment of a customers' demand to the wish date
	B1 Actual lead time	It is the actual between products is ordered and when it arrives
	B2 Inventory level	The current amount of products that a business has in stock
	B3 Packaging quality	Packing of goods with optimum safety and aesthetics
	B4 Delivery time	Average time between receiving the orders and shipping the final products
	B5 Shipment accuracy	The degree of agreement between the quantity and type of stock keeping units as indicated on the order form and as are present in the given shipment
3	Employee (C)	An individual who works part time or full time under the employment contract
	C1 Decision making skills	Making a choice between different alternatives through cognitive process
	C2 Percentage of experienced workers	Availability of trained workers to perform jobs efficiently
	C3 Interpersonal skills	Worker's ability to work and interact positively with co-workers
	C4 Management skills	Achieving certain goals with set of activities in harmony with certain policies
	C5 Training hours per week	Average training expenditure per employee
4	Flexibility (D)	Ability of a system in responding to uncertainties by varying its output, cost effectively in certain range and within fixed frame of time
	D1 Expansion flexibility	The ease with which capacity and capability of a system can be increased
	D2 Machine flexibility	Ease with which design changes can be done to a given set of parts
	D3 Process flexibility	Ease with which different products can be processed
	D4 Volume flexibility	Cost effective change in the output of a system
	D5 Routing flexibility	Flexibility in adopting different routes when machine break down
5	Productivity (E)	It is the ratio of output over per unit input
	E1 Assembly line efficiency	It is the utilization of line. It is measured in terms of ratio between the sum of the processing times and the product of cycle time and number of machines
	E2 Equipment effectiveness	Actual output over the reference output
	E3 Labour productivity	It means the amount of products that a worker can produce in a given time frame
	E4 Machine utilization	The percentage of uptime for a machine
	E5 Supply chain management	It is the management of materials, operations, finances and final products
6	Quality (F)	It is the conformance to the intended functions
	F1 Customer complaints	It is the expression displeasure by the customer
	F2 Defect/scrap ratio	Percentage of parts that cannot be repaired or resorted
	F3 First pass yield	It is the ratio of quality parts to the total number of parts produced by a machine
	F4 Rejection rate	Percentage of parts that are being rejected
	F5 Unfulfilled customer orders	Lost sales
7	Sustainability (G)	Maintaining growth without significant deterioration of the environment and depletion of natural resources
	G1 Percentage of female	Percentage of the female employees
	G2 Emission rate	It is the product of concentration and ventilation rate
	G3 Energy use	It is the minimum possible use of energy while maintaining the production rate
	G4 Turnover	Annual sales to inventory
	G5 Water use	Water use refers to use of water and water disposal by industry

Table 2 Interrelationship among subfactors



		Cost					Delivery Per					Employee					Flexibility					Productivity					Quality					Sustainability				
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	C5	D1	D2	D3	D4	D5	E1	E2	E3	E4	E5	F1	F2	F3	F4	F5	G1	G2	G3	G4	G5
Cost	A1						•	•				•	•		•	•	•	•	•		•	•	•	•	•	•			•		•				•	
	A2	•			•	•	•	•			•	•	•		•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•				•	
	A3						•		•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•			•	•	•	•	•
	A4	•					•		•	•	•		•			•						•	•	•		•	•	•	•	•					•	
	A5	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•									•	
Delivery Per	B1	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•				•	
	B2	•	•	•	•	•			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•				•	
	B3			•	•						•		•		•	•	•						•			•	•	•	•	•	•				•	
	B4	•	•	•	•	•						•	•		•	•						•	•	•		•	•	•	•	•	•				•	
	B5		•				•	•	•			•	•	•	•	•								•		•	•	•	•	•					•	
Employee	C1														•																				•	
	C2	•				•	•		•					•		•						•	•	•	•	•	•	•	•	•	•				•	
	C3														•									•		•									•	
	C4																							•		•									•	
	C5	•		•			•		•				•									•	•	•	•	•		•	•						•	
Flexibility	D1	•	•	•	•	•	•	•							•	•		•	•	•	•	•	•	•	•	•					•				•	
	D2	•	•				•	•								•						•	•	•	•	•					•				•	
	D3	•	•	•	•	•	•						•			•						•	•	•	•										•	
	D4		•	•			•		•							•	•						•	•	•	•					•				•	
	D5	•	•			•	•	•					•		•	•						•	•	•	•						•				•	
Productivity	E1	•		•		•	•						•		•	•		•						•	•			•	•						•	
	E2			•		•	•															•						•	•						•	
	E3						•	•					•				•					•	•		•						•				•	
	E4	•	•	•	•	•	•	•					•			•						•		•		•									•	
	E5			•			•			•			•		•								•		•		•				•				•	
Quality	F1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•				•	
	F2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•				•	
	F3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•				•	
	F4	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•				•	
	F5	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•					•	
Sustainability	G1			•																																
	G2			•																																
	G3			•												•										•										
	G4	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•
	G5			•																																

Fig. 3 ANP network



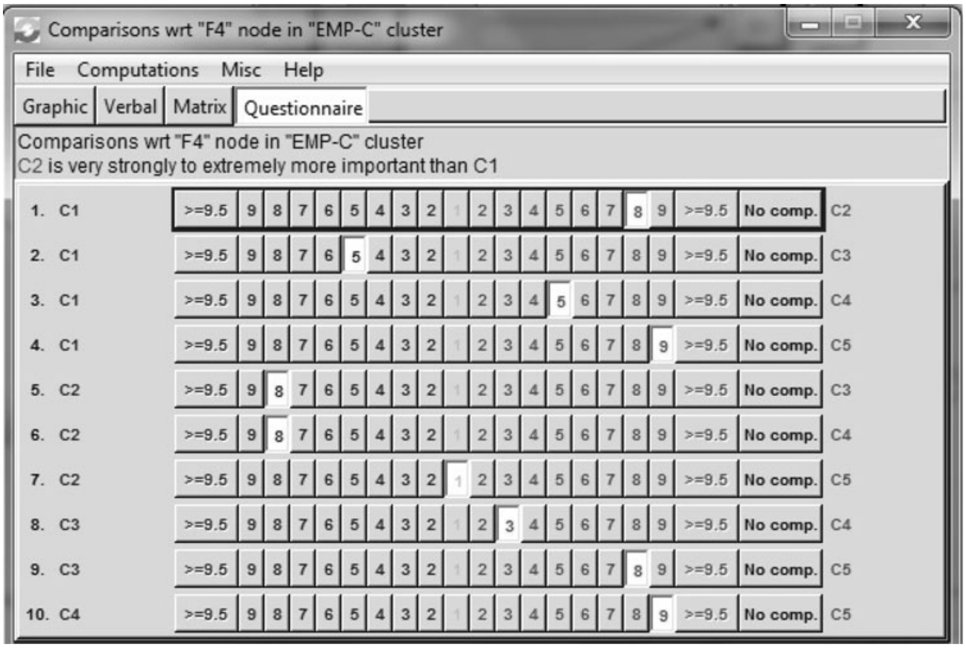
These digraphs are then transformed into matrix form for calculation purpose. Diagonal elements of the cluster matrix are the corresponding scores of the organisations for subfactors whereas off diagonal elements are the interrelationships of the subfactors taken from weighted supermatrix matrix as in Table 4. To calculate Permanent function, Eq. 2 is modified for 5 × 5 matrix, as subfactors are five in each cluster. For demonstration purpose, only calculation of permanent function for productivity cluster of organisation ‘A’ is discussed here. Digraph of the productivity cluster is shown in Fig. 5 and the corresponding matrix is shown in Eq. 3.

The permanent function of the Eq. 3 is 346.508. In the similar way, permanent of each cluster for organisation ‘A’ is calculated and is shown in Table 7.

As the final step towards the calculation of MSEI, the digraph and the matrix of clusters for organisation ‘A’ are formed. The final manufacturing system effectiveness matrix (MSEM) is shown by Eq. 4.

$$
MSEM = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \end{array}
\begin{array}{c}
\begin{array}{ccccccc} A & B & C & D & E & F & G \end{array} \\
\left[\begin{array}{ccccccc}
226.1 & 0.326 & 0.064 & 0.160 & 0.118 & 0.163 & 0.117 \\
0.05 & 774.3 & 0.039 & 0.108 & 0.059 & 0.142 & 0.068 \\
0.102 & 0.076 & 693.2 & 0.084 & 0.151 & 0.142 & 0.151 \\
0.07 & 0.079 & 0 & 68.9 & 0.096 & 0.128 & 0.094 \\
0.173 & 0.156 & 0.159 & 0.170 & 346.5 & 0.142 & 0.204 \\
0.178 & 0.130 & 0.159 & 0.167 & 0.217 & 624.4 & 0.204 \\
0.168 & 0.087 & 0.413 & 0.178 & 0.131 & 0.137 & 351.6
\end{array}\right]
\end{array} \tag{4}
$$

Fig. 4 Questionnaire



Comparisons wrt "F4" node in "EMP-C" cluster
C2 is very strongly to extremely more important than C1

1.	C1	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	>=9.5	No comp.	C2
2.	C1	>=9.5	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	C3
3.	C1	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	>=9.5	No comp.	C4
4.	C1	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	>=9.5	No comp.	C5
5.	C2	>=9.5	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	C3
6.	C2	>=9.5	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	C4
7.	C2	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	C5
8.	C3	>=9.5	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	>=9.5	No comp.	C4
9.	C3	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	>=9.5	No comp.	C5
10.	C4	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	>=9.5	No comp.	C5

The off diagonal members of MSEM in Eq. 4 are taken from cluster matrix as in Table 7. The diagonal members of the MSEM are taken as permanent values as shown in Table 8. MSEI is calculated as the permanent of MSEM, which is calculated by modifying Eq. 2 for 7 × 7 matrix.

MSEI = per MSEM for organisation 'A' = 6.33×10^{17}

By following the same procedure, MSEI is calculated for organisations 'B' and 'C'.

MSEI for organisation 'B' = 3.56×10^{17}.

MSEI for organisation 'C' = 1.2×10^{17}.

2.5.1 *Validation*

Permanent function values for each cluster along with MSEI for organisations A, B and C are shown in Table 9.

Table 10 shows the data collected for each organisation from the 2010 financial reports and from a shareholders' conference in the first half of 2011. To maintain confidentiality, instead of data only ratios of best values are given. '1' represents the best value in that factor.

MSEI from Table 9 suggest organisation 'A' has best performance and the same is validated by the actual data as shown in Table 10.

3 Results and discussions

In this study, combined approach of ANP and GTMA is proposed to evaluate the effectiveness of a manufacturing system. This will help managers to better understand the adoption of new technologies, comparing performance internally as well as with their competitors. Critical factors that were used in the model focused on manufacturing system strategy. ANP approach is used to prioritize the factors. It evaluates both quantitative as well as qualitative factors.

Effectiveness evaluation model has 7 main factors (cost, delivery performance, employee, flexibility, productivity, quality and sustainability) and 35 subfactors. The top five subfactors are Turnover (13.885 %), Supply Chain

Table 3 A portion of unweighted supermatrix

	COST-A					DLP-B					EMP-C				
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	C5
COST-A															
A1	0	0.74	0	1	0.653	0.449	0.16	0	0.175	0	0	0.587	0	0	0.857
A2	0	0	0	0	0.058	0.096	0.516	0	0.091	1	0	0	0	0	0
A3	0	0	0	0	0.234	0.113	0.059	0.111	0.081	0	0	0	0	0	0.143
A4	0	0.094	0	0	0.055	0.23	0.195	0.889	0.56	0	0	0	0	0	0
A5	0	0.167	0	0	0	0.112	0.07	0	0.094	0	0	0.413	0	0	0
DLP-B															
B1	0.778	0.07	0.648	0.364	0.564	0	0.219	0	0	0.566	0	0.875	0	0	0.857
B2	0.222	0.707	0	0	0.182	0.207	0	0	0	0.061	0	0	0	0	0
B3	0	0	0.122	0.348	0.042	0.038	0.042	0	0	0.373	0	0.125	0	0	0.143
B4	0	0	0	0.109	0.098	0.056	0.065	0	0	0	0	0	0	0	0
B5	0	0.223	0.23	0.18	0.114	0.699	0.674	1	0	0	0	0	0	0	0
EMP-C															
C1	0.046	0.087	0.073	0	0.087	0.057	0.399	0	0.037	0.062	0	0	0	0	0
C2	0.494	0.408	0.443	0.636	0.458	0.445	0.079	0.571	0.369	0.364	0	0	0	0	1
C3	0	0	0.076	0	0.061	0.029	0.031	0	0	0.044	0	0.111	0	0	0
C4	0.193	0.408	0.112	0	0.03	0.142	0.41	0.143	0.096	0.219	1	0	1	1	0
C5	0.266	0.097	0.297	0.364	0.364	0.327	0.082	0.286	0.498	0.31	0	0.889	0	0	0
FLXT-D															
D1	0.041	0.042	0.059	0	0.032	0.244	0.036	1	0	0	0	0	0	0	0
D2	0.517	0.424	0.379	0	0.414	0.215	0.443	0	0	0	0	0	0	0	0
D3	0.204	0	0.3	0	0.312	0.183	0.223	0	0	0	0	0	0	0	0
D4	0	0.179	0.065	0	0.052	0.183	0.049	0	0	0	0	0	0	0	0
D5	0.238	0.356	0.198	0	0.19	0.174	0.249	0	0	0	0	0	0	0	0
PRO-E															
E1	0.169	0.225	0.152	0.227	0.13	0.154	0.144	0.333	0.25	0	0	0.043	0	0	0.232
E2	0.126	0.097	0.152	0.227	0.349	0.305	0.366	0.333	0.25	0	0	0.046	0	0	0.175
E3	0.146	0.048	0.153	0.122	0.141	0.115	0.044	0	0.25	0.111	0	0.092	0.125	0.25	0.198
E4	0.142	0.124	0.112	0	0.17	0.081	0.226	0	0	0	0	0.401	0	0	0.198
E5	0.417	0.506	0.43	0.424	0.21	0.345	0.22	0.333	0.25	0.889	0	0.419	0.875	0.75	0.198
QLT-F															
F1	0	0.162	0.167	0.14	0	0.051	0.062	0.357	0.109	0.638	0	0	0	0	0
F2	0	0.309	0	0.232	0	0.307	0.501	0.062	0.121	0.146	0	0.174	0	0	0.167
F3	0.875	0.285	0.833	0.395	0	0.217	0.233	0.221	0.62	0	0	0.594	0	0	0.833
F4	0	0.179	0	0.232	0	0.316	0.174	0.259	0.119	0.098	0	0.157	0	0	0
F5	0.125	0.066	0	0	0	0.109	0.031	0.101	0.032	0.118	0	0.074	0	0	0
SUS-G															
G1	0	0	0.039	0	0	0	0	0	0	0	0	0	0	0	0
G2	0	0	0.107	0	0	0	0	0	0	0	0	0	0	0	0
G3	0	0	0.162	0	0	0	0	0	0	0	0	0	0	0	0
G4	1	1	0.646	1	0	1	1	1	1	1	0	0	1	0	1
G5	0	0	0.046	0	0	0	0	0	0	0	0	0	0	0	0

	FLXT-D					PRO-E					QLT-F		
	D1	D2	D3	D4	D5	E1	E2	E3	E4	E5	F1	F2	F3
COST-A													
A1	0.343	0.167	0.198	0	0.732	0.652	0	0	0.489	0	0.454	0.056	0.043

Table 3 continued

	FLXT-D					PRO-E					QLT-F		
	D1	D2	D3	D4	D5	E1	E2	E3	E4	E5	F1	F2	F3
A2	0.176	0.833	0.133	0.256	0.138	0	0	0	0.223	0	0.18	0.057	0.078
A3	0.201	0	0.411	0.454	0	0.113	0.243	0	0.078	1	0.176	0.182	0.1
A4	0	0	0	0	0	0	0	0	0	0	0.1	0.586	0.278
A5	0.28	0	0.258	0.289	0.13	0.235	0.757	1	0.21	0	0.091	0.12	0.501
DLP-B													
B1	0.401	0.79	1	0	0.833	1	1	1	0.8	0.857	0.304	0.241	0.315
B2	0.599	0.21	0	1	0.167	0	0	0	0.2	0	0.067	0.061	0.297
B3	0	0	0	0	0	0	0	0	0	0	0.049	0.046	0.028
B4	0	0	0	0	0	0	0	0	0	0.143	0.22	0.53	0.062
B5	0	0	0	0	0	0	0	0	0	0	0.359	0.123	0.297
EMP-C													
C1	0	0	0	0	0	0	0	0	0	0	0.049	0.051	0.081
C2	0	0	0.8	0	0.773	0.466	0	0.5	0.5	0.875	0.467	0.468	0.401
C3	0	0	0	0	0	0	0	0	0	0	0.032	0.033	0.026
C4	0.477	0	0	0	0.088	0.1	0	0	0	0.125	0.102	0.107	0.073
C5	0.523	1	0.2	1	0.139	0.433	0	0.5	0.5	0	0.35	0.341	0.42
FLXT-D													
D1	0	0	0	1	0	0	0	0	0	0	0.076	0.036	0.033
D2	0.62	0	0	0	0	1	0	0	0	0	0.318	0.428	0.395
D3	0.175	0	0	0	0	0	0	0	0	0	0.371	0.278	0.304
D4	0.04	0	0	0	0	0	0	0	0	0	0.038	0.049	0.054
D5	0.165	0	0	0	0	0	0	0	0	0	0.197	0.209	0.213
PRO-E													
E1	0.14	0.2	0.333	0	0.237	0	1	0.5	0.212	0	0.136	0.041	0.225
E2	0.107	0.2	0.333	0.379	0.197	0	0	0.25	0	0.5	0.443	0.457	0.241
E3	0.069	0.2	0.167	0.161	0.149	0.5	0	0	0.079	0	0.26	0.34	0.241
E4	0.493	0.2	0.167	0.23	0.417	0.5	0	0.25	0	0.5	0.041	0.069	0.25
E5	0.192	0.2	0	0.23	0	0	0	0	0.709	0	0.121	0.094	0.043
QLT-F													
F1	0	0	0	0	0	0	0	0	0	0	0	0.15	0.228
F2	0	0	0	0	0	0.5	0.2	0	0	0.857	0.207	0	0.346
F3	0	0	0	0	0	0.5	0.8	0	0	0	0.24	0.504	0
F4	0	0	0	0	0	0	0	0	0	0	0.376	0.26	0.322
F5	0	0	0	0	0	0	0	0	0	0.143	0.177	0.085	0.103
SUS-G													
G1	0	0	0	0	0	0	0	0	0	0	0	0	0
G2	0	0	0	0	0	0	0	0	0	0	0	0	0
G3	0	0	0	0	0	0	0	0	0	0	0	0	0
G4	1	1	1	1	1	1	1	1	1	1	1	1	1
G5	0	0	0	0	0	0	0	0	0	0	0	0	0

Management (6.7 %), First Pass Yield (5.8 %), Percentage of Experienced Workers (5.5 %) and Management Skills (4.8 %). These subfactors play an important role in evolution of effectiveness. The study here proposes the use of GTMA for evaluating numerical index, which will give the overall effectiveness in a single numerical value. With its help, managers would be able to analyse that how much improvement in one factor will improve the overall effectiveness.

Table 4 A portion of weighted supermatrix

	COST-A					DLP-B					EMP-C				
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	C5
COST-A															
A1	0	0.184	0	0.27	0.249	0.147	0.052	0	0.073	0	0	0.038	0	0	0.055
A2	0	0	0	0	0.022	0.031	0.169	0	0.038	0.355	0	0	0	0	0
A3	0	0	0	0	0.089	0.037	0.019	0.036	0.034	0	0	0	0	0	0.009
A4	0	0.023	0	0	0.021	0.075	0.064	0.29	0.235	0	0	0	0	0	0
A5	0	0.041	0	0	0	0.037	0.023	0	0.039	0	0	0.026	0	0	0
DLP-B															
B1	0.052	0.004	0.043	0.02	0.043	0	0.031	0	0	0.088	0	0.035	0	0	0.034
B2	0.015	0.036	0	0	0.014	0.03	0	0	0	0.01	0	0	0	0	0
B3	0	0	0.008	0.019	0.003	0.005	0.006	0	0	0.058	0	0.005	0	0	0.006
B4	0	0	0	0.006	0.008	0.008	0.009	0	0	0	0	0	0	0	0
B5	0	0.011	0.015	0.01	0.009	0.1	0.097	0.143	0	0	0	0	0	0	0
EMP-C															
C1	0.006	0.009	0.01	0	0.014	0.004	0.031	0	0.004	0.005	0	0	0	0	0
C2	0.067	0.042	0.06	0.071	0.072	0.034	0.006	0.044	0.036	0.03	0	0	0	0	0.165
C3	0	0	0.01	0	0.01	0.002	0.002	0	0	0.004	0	0.018	0	0	0
C4	0.026	0.042	0.015	0	0.005	0.011	0.032	0.011	0.01	0.018	1	0	0.508	0.508	0
C5	0.036	0.01	0.04	0.04	0.057	0.025	0.006	0.022	0.049	0.026	0	0.146	0	0	0
FLXT-D															
D1	0.004	0.003	0.006	0	0.004	0.019	0.003	0.079	0	0	0	0	0	0	0
D2	0.054	0.033	0.04	0	0.05	0.017	0.035	0	0	0	0	0	0	0	0
D3	0.021	0	0.031	0	0.037	0.015	0.018	0	0	0	0	0	0	0	0
D4	0	0.014	0.007	0	0.006	0.015	0.004	0	0	0	0	0	0	0	0
D5	0.025	0.028	0.021	0	0.023	0.014	0.02	0	0	0	0	0	0	0	0
PRO-E															
E1	0.039	0.039	0.035	0.043	0.035	0.024	0.023	0.052	0.05	0	0	0.007	0	0	0.037
E2	0.029	0.017	0.035	0.043	0.093	0.048	0.057	0.052	0.05	0	0	0.007	0	0	0.028
E3	0.034	0.008	0.035	0.023	0.037	0.018	0.007	0	0.05	0.019	0	0.015	0.061	0.123	0.031
E4	0.033	0.022	0.026	0	0.045	0.013	0.035	0	0	0	0	0.064	0	0	0.031
E5	0.096	0.088	0.099	0.08	0.056	0.054	0.034	0.052	0.05	0.151	0	0.067	0.43	0.369	0.031
QLT-F															
F1	0	0.029	0.04	0.027	0	0.007	0.008	0.046	0.018	0.09	0	0	0	0	0
F2	0	0.055	0	0.045	0	0.04	0.065	0.008	0.02	0.021	0	0.028	0	0	0.027
F3	0.028	0.051	0.198	0.077	0	0.028	0.03	0.029	0.104	0	0	0.095	0	0	0.133
F4	0	0.032	0	0.045	0	0.041	0.023	0.034	0.02	0.014	0	0.025	0	0	0
F5	0.03	0.012	0	0	0	0.014	0.004	0.013	0.005	0.017	0	0.012	0	0	0
SUS-G															
G1	0	0	0.009	0	0	0	0	0	0	0	0	0	0	0	0
G2	0	0	0.024	0	0	0	0	0	0	0	0	0	0	0	0

Table 4 continued

	COST-A					DLP-B					EMP-C				
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	C5
G3	0	0	0.036	0	0	0	0	0	0	0	0	0	0	0	0
G4	0.225	0.169	0.145	0.183	0	0.088	0.088	0.088	0.113	0.095	0	0.413	0	0	0.413
G5	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0

	FLXT-D					PRO-E					QLT-F
	D1	D2	D3	D4	D5	E1	E2	E3	E4	E5	F1
COST-A											
A1	0.067	0.031	0.037	0	0.135	0.077	0	0	0.084	0	0.074
A2	0.034	0.154	0.024	0.041	0.025	0	0	0	0.038	0	0.029
A3	0.039	0	0.076	0.073	0	0.013	0.038	0	0.013	0.131	0.029
A4	0	0	0	0	0	0	0	0	0	0	0.016
A5	0.055	0	0.048	0.046	0.024	0.028	0.119	0.131	0.036	0	0.015
DLP-B											
B1	0.053	0.099	0.125	0	0.104	0.06	0.079	0.066	0.07	0.057	0.043
B2	0.079	0.026	0	0.108	0.021	0	0	0	0.017	0	0.01
B3	0	0	0	0	0	0	0	0	0	0	0.007
B4	0	0	0	0	0	0	0	0	0	0.009	0.031
B5	0	0	0	0	0	0	0	0	0	0	0.051
EMP-C											
C1	0	0	0	0	0	0	0	0	0	0	0.007
C2	0	0	0.077	0	0.075	0.071	0	0.084	0.11	0.147	0.067
C3	0	0	0	0	0	0	0	0	0	0	0.005
C4	0.049	0	0	0	0.008	0.015	0	0	0	0.021	0.015
C5	0.054	0.097	0.019	0.084	0.013	0.066	0	0.084	0.11	0	0.05
FLXT-D											
D1	0	0	0	0.131	0	0	0	0	0	0	0.01
D2	0.099	0	0	0	0	0.096	0	0	0	0	0.041
D3	0.028	0	0	0	0	0	0	0	0	0	0.048
D4	0.006	0	0	0	0	0	0	0	0	0	0.005
D5	0.026	0	0	0	0	0	0	0	0	0	0.025
PRO-E											
E1	0.029	0.039	0.066	0	0.047	0	0.3	0.125	0.07	0	0.019
E2	0.022	0.039	0.066	0.065	0.039	0	0	0.062	0	0.125	0.063
E3	0.014	0.039	0.033	0.027	0.029	0.113	0	0	0.026	0	0.037
E4	0.102	0.039	0.033	0.039	0.082	0.113	0	0.062	0	0.125	0.006
E5	0.04	0.039	0	0.039	0	0	0	0	0.233	0	0.017
QLT-F											
F1	0	0	0	0	0	0	0	0	0	0	0
F2	0	0	0	0	0	0.109	0.058	0	0	0.206	0.03
F3	0	0	0	0	0	0.109	0.231	0	0	0	0.034

Table 4 continued

	FLXT-D					PRO-E					QLT-F
	D1	D2	D3	D4	D5	E1	E2	E3	E4	E5	F1
F4	0	0	0	0	0	0	0	0	0	0	0.054
F5	0.204	0.193	0.193	0.167	0.193	0	0	0.24	0	0.034	0.025
SUS-G											
G1	0	0	0	0	0	0	0	0	0	0	0
G2	0	0	0	0	0	0	0	0	0	0	0
G3	0	0	0	0	0	0	0	0	0	0	0
G4	0	0.205	0.205	0.178	0.205	0.131	0.174	0.145	0.191	0.145	0.138
G5	0	0	0	0	0	0	0	0	0	0	0

Table 5 A portion of limit matrix

	COST-A					DLP-B					EMP-C				
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	C5
COST-A															
A1	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
A2	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021
A3	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043
A4	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
A5	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
DLP-B															
B1	0 039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
B2	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
B3	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
B4	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
B5	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
EMP-C															
C1	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
C2	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055
C3	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
C4	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049

Table 5 continued

	COST-A					DLP-B					EMP-C				
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	C5
C5	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
FLXT-D															
D1	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
D2	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
D3	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
D4	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
D5	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
PRO-E															
E1	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
E2	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
E3	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
E4	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
E5	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068
QLT-F															
F1	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
F2	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
F3	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
F4	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
F5	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
SUS-G															
G1	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04
G2	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
G3	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
G4	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139
G5	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008

	FLXT-D					PRO-E					QLT-F
	D1	D2	D3	D4	D5	E1	E2	E3	E4	E5	F1
COST-A											
A1	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
A2	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021
A3	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043
A4	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
A5	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
DLP-B											
B1	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
B2	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
B3	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
B4	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
B5	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015

Table 5 continued

	FLXT-D D1	D2	D3	D4	D5	PRO-E E1	E2	E3	E4	E5	QLT-F F1
EMP-C											
C1	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
C2	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055
C3	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
C4	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049
C5	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
FLXT-D											
D1	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
D2	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
D3	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0 013
D4	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
D5	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
PRO-E											
E1	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
E2	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
E3	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
E4	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
E5	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068
QLT-F											
F1	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
F2	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
F3	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
F4	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
F5	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
SUS-G											
G1	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04	4E−04
G2	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
G3	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
G4	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139
G5	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008

Table 6 Priority matrix

Name		Normalized by cluster	Limiting	Rank	Score of A	Score of B	Score of C
A1	Cost of downtime/maintenance	0.28641	0.045081	6	2.8	2.0	2.2
A2	Cost of inventory	0.1336	0.021028	19	2.5	3.0	1.8
A3	Operating cost	0.27127	0.042698	8	4.6	4.0	2.0
A4	Cost of Scrap/rework	0.13832	0.021772	18	3.9	3.8	3.0
A5	WIP cost	0.17041	0.026822	16	1.8	2.1	2.2
B1	Actual lead time	0.49002	0.038996	11	4.7	4.1	1.5
B2	Inventory level	0.1385	0.011022	25	2.3	1.5	3.3
B3	Packaging quality	0.06838	0.005442	33	4.5	3.9	2.4
B4	Delivery time	0.11366	0.009045	26	3.6	3.0	2.2
B5	Shipment accuracy	0.18944	0.015076	21	4.4	4.0	2.2
C1	Decision making skills	0.04614	0.007524	30	4.6	4.2	2.5
C2	Percentage of experienced workers	0.33969	0.055397	4	3.3	2.8	2.4
C3	Interpersonal skills	0.0414	0.006751	31	3.1	2.6	2.1
C4	Management skills	0.29832	0.04865	5	4.2	4.0	2.0
C5	Training hours per week	0.27445	0.044758	7	3.5	3.0	2.0
D1	Expansion flexibility	0.10316	0.005966	32	1.8	2.1	1.8
D2	Machine flexibility	0.38815	0.022448	17	2.1	1.2	1.6
D3	Process flexibility	0.22905	0.013247	23	2.4	2.0	1.5
D4	Volume flexibility	0.19267	0.011143	24	2.0	1.8	1.4
D5	Routing flexibility	0.08697	0.00503	34	3.8	3.0	2.4
E1	Assembly line efficiency	0.18215	0.039306	9	2.7	2.0	1.8
E2	Equipment effectiveness	0.17314	0.037361	12	3.2	3.0	2.2
E3	Labour productivity	0.16	0.034525	14	3.3	3.3	1.2
E4	Machine utilization	0.17067	0.036828	13	3.1	3.4	2.4
E5	Supply chain management	0.31404	0.067765	2	3.9	2.5	2.2
F1	Customer complaints	0.09041	0.014657	22	4.2	3.8	1.8
F2	Defect/scrap ratio	0.2407	0.039022	10	3.4	3.0	1.8
F3	First pass yield	0.36392	0.058998	3	2.8	2.2	2.2
F4	Rejection rate	0.10408	0.016873	20	4.0	2.0	1.8
F5	Unfulfilled customer orders	0.2009	0.03257	15	3.9	2.5	1.4
G1	Percentage of female	0.00231	0.000379	35	1.8	2.4	1.2
G2	Emission rate	0.05074	0.008331	28	3.4	2.4	1.4
G3	Energy use	0.05396	0.008861	27	3.8	2.4	1.6
G4	Turnover	0.84581	0.138883	1	4.2	2.6	2.0
G5	Water use	0.04718	0.007747	29	3.6	2.2	2.4

Table 7 Cluster matrix

	COST-A	DLP-B	EMP-C	FLXT-D	PRO-E	QLT-F	SUS-G
COST-A	0.248605	0.326466	0.064096	0.160245	0.118243	0.163732	0.117792
DLP-B	0.050297	0.143222	0.039699	0.108412	0.059731	0.142437	0.068991
EMP-C	0.102107	0.076845	0.164663	0.084226	0.151563	0.142437	0.151594
FLXT-D	0.078384	0.079133	0	0.130695	0.096389	0.128915	0.094487
PRO-E	0.173228	0.156685	0.159187	0.170928	0.2259	0.142437	0.20463
QLT-F	0.17857	0.130044	0.15916	0.167404	0.217146	0.142437	0.20463
SUS-G	0.168809	0.087606	0.413196	0.17809	0.131027	0.137606	0.157874

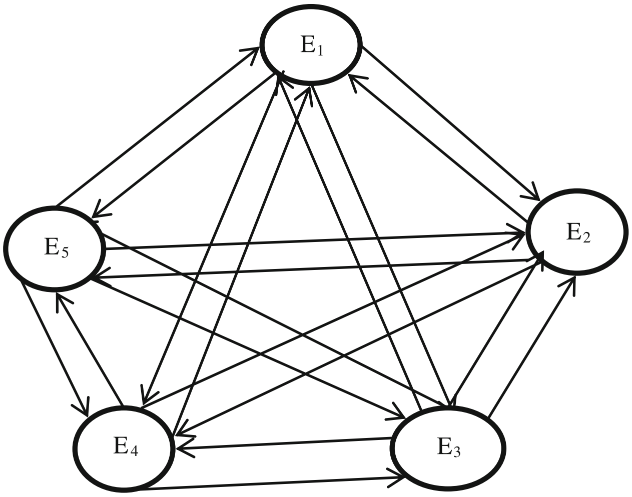


Fig. 5 Productivity cluster digraph

Table 8 Permanent function values of each cluster

S. no.	Name of cluster	Permanent function value
1	Cost	226.089
2	Delivery performance	771.333
3	Employee	693.195
4	Flexibility	68.922
5	Productivity	346.508
6	Quality	624.427
7	Sustainability	351.631

Table 9 Permanent function values

Name	Organisation 'A'	Organisation 'B'	Organisation 'C'
Cost	226.08	150.23	102.12
Delivery performance	771.33	456.12	342.26
Employee	693.19	485.26	402.12
Flexibility	68.92	42.56	28.56
Productivity	346.50	254.28	154.23
Quality	624.42	356.12	312.56
Sustainability	351.63	302.15	152.26
MSEI	6.33×10^{17}	3.56×10^{17}	1.2×10^{17}

Table 10 Performance of the organisations

	A	B	C
Market share	1	0.59	0.36
Yield per head	1	0.64	0.69
Gross profit margin	1	0.46	0.45
Earnings per share	1	0.15	0.07
Average inventory turnover	0.98	0.80	1

4 Conclusions

In the previous studies (Yang et al. 2009; Çelebi et al. 2010; Vinodh et al. 2011) researchers have tried to find the overall index by simply adding the product of factors' weights with the organisations' performance (on Likert scale). This ignores the interrelationships of the factors, which is rather unusual for this kind of problems. In this study, GTMA takes into account the interrelations while calculating the Manufacturing System Evaluation Index (MSEI). The results are verified by conducting case studies in three organisations. Managers can easily compare their system's performance with their peers. Authors feel that this study will help managers for continuously improving their system. The sensitivity analysis can also be performed by changing the pairwise comparison values to see the stability of the model.

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