

## The Tchebycheff Norm for Ranking DMUs in Cellular Manufacturing Systems with Assignment Worker

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**Abstract** This paper develops an integer mathematical programming model to design the cellular manufacturing systems under data envelopment analysis. Since workers have an important role in doing jobs on machines, assignment of workers to cells becomes a crucial factor for fully utilization of cellular manufacturing systems (CMS). The aim of the proposed is to minimize backorder costs and intercellular costs. The Data Envelopment Analysis (DEA) is performed to determine the most efficient alternative among alternatives that considered by employing the average machine utilization, the average worker utilization, the number of product as the output variables and the number of machines, the number of workers, the number of parts and demand levels as the input variables. We are using the Tchebycheff norm method to rank the best DMUs.

**Keywords** Mathematical Programming, Manufacturing System, Data Envelopment Analysis.

### 1 Introduction

Group technology (GT) is a manufacturing philosophy in which similar parts are identified and grouped together to take advantages of their similarities in manufacturing and design. GT was first proposed by Mitrofanov [1], and was propagated by Burbidge [2], who developed methods suitable for hand computation. Cellular manufacturing (CM) is a successful application of GT concepts. The major advantages of CM have been reported in the literature as reduction in setup time, reduction in throughput time, reduction in work-in-process inventories, reduction in material handling costs, better quality and production control, increment in flexibility, etc. (Heragu [3], Wemmerlov and Hyer [4]). One of the key issues encountered in the implementation of a CMS is the cell formation problem (CFP). In the past several years, many solution methods have been developed for solving cell formation problem (CFP) by a binary machine-part incidence (two-dimensional) matrix. Some comprehensive summaries and taxonomies considering the CFP as a machine-part incidence matrix include Singh [5], Offodile et al. [6], Selim et al. [7] and Mansouri et al. [8]. Moreover, recently some approaches that have been developed to the two-dimensional CFP are: genetic algorithms (Goncalves and Resende [9] and Mahdavi et al. [10]), tabu search (Lozano et al. [11] and Wu et al. [12]), neural network (Soleymanpour et al. [13]), mathematical programming (Albadawi

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et al. [14] and Mahdavi et al. [15]), simulated annealing (Wu et al. [16] and Pailla et al. [17]) and similarity coefficients-based method (Yin and Yasuda [18] and Oliveira et al. [19]).

One of the main points in CM is considering human issues since ignoring this factor can considerably reduce benefits of the utility of the cell manufacturing. In some of the previous research papers this issue is discussed. Nembhard [20] described a greedy heuristic approach based on individual learning rate for the improvement of productivity in organizations through targeted assignment of workers to tasks. Norman et al. [21] proposed a mixed integer programming model for assigning workers to manufacturing cells in order to maximize the profit. Bidanda et al. [22] presented an overview and evaluation of the diverse range of human issues involved in CM based on an extensive literature review. In Wirojanagud et al. [23] a workforce planning model that incorporates individual worker differences in ability to learn new skills and perform tasks was presented. The model allows a number of different staffing decisions (i.e., hire and fire) in order to minimize workforce related and missed production costs. Aryanezhad et al. [24] presented a new model to deal with dynamic cell formation and worker assignment problem with considering part routing flexibility and machine flexibility and also promotion of workers from one skill level.

Min and Shin [25] created a prototype of three-dimensional GT. Their method was to insert the third factor, operator, into the sorted incidence matrix of parts and machines. Parkin and Li [26] proposed an algorithm for N-dimensional GT. Their algorithm focused on each incidence matrix, sorting each separately. Li [27] showed a method of solving multi-dimensional GT problem. Mahdavi et al. [10] presented a new mathematical model to minimize the number of voids and exceptional elements in a three dimensional (cubic) machine-part-worker incidence matrix. One important aspect of the cell formation problem is its efficiency measurement procedures. Besides, there are few researches on the efficiency measurement of the cell formation. Especially, very little CMS research has been directed at human factor issues (Scott et al., [28]). Ertay and Ruan [29] took advantage of the cross-efficiency evaluation to determine the best labor assignment in CMS. Their study concentrates on efficiency measurement and the determination of the number of operators in CMS when the demand rate and the transfer batch size as a rate of batch size change. Both the inputs and outputs of their study were procured by means of simulation of CMS.

In this paper we develop an integer mathematical programming to design the CMS, by means of considering several situation for each of input variables, the number of machines, the number of workers, the number of parts and demand levels, we get several different alternatives to decision maker. To determine the most efficient alternative, for each alternative we use the developed CMS model to gain the average machine utilization, the average worker utilization, and mean of product as the output variables of the alternative and then DEA performed to determine the most efficient scenario among all the scenarios that considered.

## 2 Data envelopment analysis methodology

Data envelopment analysis (DEA), proposed by Charnes et al. [30] is a mathematical programming technique that measures the relative efficiency of decision making units (DMUs) with multiple inputs and outputs but with no obvious production function to aggregate the data in its entirety. In most models of DEA (such as CCR), the best performers have efficiency score unity, and, from experience, we know that usually there are plural DMUs which have this “efficient status”. To discriminate between these efficient DMUs is an interesting research subject. Ranking DMUs is one of the main problems in DEA. Several

authors have proposed methods for ranking the best performers. See for example Adler et al. [31].

Recently, several authors have proposed some methods based on norms. Jahanshahloo et al. [32] introduced  $L_1$ -norm approach and Rezai balf et al. [33] presented ranking model  $L_\infty$ -norm (or Tchebycheff norm) in data envelopment analysis. In this paper, we are use the ranking method based on the tchebycheff norm proposed by Rezai balf et al. [33] that it seems to have superiority over other existing methods, because this method is able to remove the existing deficiencies in some methods, such as Anderson and Peterson [34] that it is sometimes infeasible. The  $L_\infty$ -norm model always is feasible.

## 2.1 Background DEA

### 2.1.1 DEA model

DEA is a mathematical model that measures the relative efficiency of decision making units (DMUs) with multiple inputs and outputs but with no obvious production function to aggregate the data in its entirety. By comparing  $n$  units with  $s$  outputs denoted by  $y_{rj}$  ( $r = 1, \dots, s$ ), and  $m$  inputs denoted by  $x_{ij}$  ( $i = 1, \dots, m$ ), that all of them are non-negative and each DMU has at least one strictly positive input and output. The efficiency of a specific DMU<sub>p</sub> can be evaluated by the CCR model (Charnes et al. [30]), of DEA as follows:

$$\begin{aligned}
 & \text{Max} \quad \frac{\sum_{r=1}^s u_r y_{ro}}{\sum_{i=1}^m v_i x_{io}} \\
 & \text{s.t.} \quad \frac{\sum_{r=1}^s u_r y_{rj}}{\sum_{i=1}^m v_i x_{ij}} \leq 0, \quad j = 1, \dots, n, \\
 & \quad u_r \geq 0, \quad r = 1, \dots, s, \\
 & \quad v_i \geq 0, \quad i = 1, \dots, m.
 \end{aligned} \tag{1}$$

where  $u_r$  ( $r = 1, \dots, s$ ), and  $v_i$  ( $i = 1, \dots, m$ ), represent the output and input weights, respectively.

Besides, the fractional program is not used for actual computation of the efficiency scores due to its non-convex and nonlinear properties. Hence, by using Charnes and Cooper [35] transformation, model 1 can be equivalently transformed into the linear program below for solution:

$$\begin{aligned}
& \text{Max} \sum_{r=1}^s u_r y_{ro} \\
& \text{s.t.} \\
& \sum_{i=1}^m v_i x_{io} = 1 \\
& \sum_{r=1}^s u_r y_{rj} - \sum_{i=1}^m v_i x_{ij} \leq 0, \quad j = 1, \dots, n, \\
& u_r \geq 0, \quad r = 1, \dots, s, \\
& v_i \geq 0, \quad i = 1, \dots, m.
\end{aligned} \tag{2}$$

### 2.1.2 $L_\infty$ -norm in DEA

By comparing  $n$  units with  $s$  outputs denoted by  $y_{rj}, r = 1, \dots, s$ , and  $m$  inputs denoted by  $x_{ij}, i = 1, \dots, m$ , that all of them are non-negative and each DMU has at least one strictly positive input and output. The production possibility sets (PPS) is defined as:

$$T_c = \{(X, Y) \mid X \geq \sum_{j=1}^n \lambda_j X_j, Y \leq \sum_{j=1}^n \lambda_j Y_j, \lambda_j \geq 0, j = 1, \dots, n\} \tag{3}$$

Rezai balf et al. [33] introduced ranking model  $L_\infty$ -norm in data envelopment analysis. They assumed that the DMU<sub>O</sub> is extremely efficient. By omitting  $(X_O, Y_O)$  from  $T_c$ , they defined the production possibility set  $T'_c$  as:

$$T'_c = \{(X, Y) \mid X \geq \sum_{j=1, j \neq o}^n \lambda_j X_j, Y \leq \sum_{j=1, j \neq o}^n \lambda_j Y_j, \lambda_j \geq 0, j = 1, \dots, n\} \tag{4}$$

They consider the following model to obtain the ranking score of DMU<sub>O</sub>:

$$\begin{aligned}
& \text{Min } \Phi_c^o(X, Y) = \text{Max} \left( \left\{ x_{io} - \sum_{j=1, j \neq o}^n \lambda_j x_{ij} \right\}_{i=1, \dots, m}, \left\{ y_{ro} - \sum_{j=1, j \neq o}^n \lambda_j y_{rj} \right\}_{r=1, \dots, s} \right) \\
& \text{s.t.} \\
& \sum_{j=1, j \neq o}^n \lambda_j x_{ij} \geq x_{io}, \quad i = 1, \dots, m, \\
& \sum_{j=1, j \neq o}^n \lambda_j y_{rj} \leq y_{ro}, \quad r = 1, \dots, s, \\
& \lambda_j \geq 0, \quad j = 1, \dots, n.
\end{aligned} \tag{5}$$

where  $X = (x_1, \dots, x_m)$ ,  $Y = (y_1, \dots, y_s)$  and  $\Lambda = (\lambda_1, \dots, \lambda_{o-1}, \lambda_{o+1}, \dots, \lambda_n)$  are the variables of the model 5 and  $\Phi_c^o(X, Y)$  is a distance  $(X_o, Y_o)$  from  $(X, Y)$  by using  $L_\infty$ -norm. It is obvious

that the model 5 is non-linear. In order to converting this model to a linear form, the set  $T_c''$  is defined as:

$$T_c'' = T_c' \cap \{(X, Y) | X \geq X_o, Y \leq Y_o\}.$$

Therefore, by added the constrains  $X \geq X_o$  and  $Y \leq Y_o$  to the model 5 they obtained the linear form as follows:

$$\text{Min } \varphi_o$$

s.t.

$$\varphi_o \geq \sum_{j=1, j \neq o}^n \lambda_j x_{ij} - x_{io}, \quad i = 1, \dots, m, \quad (6)$$

$$\varphi_o \geq y_{ro} - \sum_{j=1, j \neq o}^n \lambda_j y_{rj}, \quad r = 1, \dots, s,$$

$$\lambda_j \geq 0, \quad j = 1, \dots, n.$$

$$\text{where } \varphi_o = \text{Max} \left( \left\{ \sum_{j=1, j \neq o}^n \lambda_j x_{ij} - x_{io} \right\}_{i=1, \dots, m}, \left\{ y_{ro} - \sum_{j=1, j \neq o}^n \lambda_j y_{rj} \right\}_{r=1, \dots, s} \right).$$

**Theorem 1.** Suppose  $(X_o, Y_o) \in T_c$  is extreme efficient. For each  $(\bar{X}, \bar{Y}) \in T_c' \setminus T_c''$  there exists at least a member of  $T_c''$ , say  $(\tilde{X}, \tilde{Y})$ , such that  $\Phi_c^o(\tilde{X}, \tilde{Y}) \leq \Phi_c^o(\bar{X}, \bar{Y})$ .

**Theorem 2.** In any optimal solution the model 6, at least one of inputs (outputs) constraints is active.

**Theorem 3.** The projected point of  $DMU_o$  in model 6 lies on the efficient frontier.

**Theorem 4.** Model 6 is always feasible and bounded.

### 3 Problem formulation

In this section, the mathematical model has been presented based on CMS with worker flexibility under following assumptions:

- The processing time for all operations of a part type on different machine types are known and deterministic.
- The demand for each part type is known and deterministic.
- The capacity of each machine type is known
- The available time of each worker is known
- The number of production for each part littler than the number of demand for each part.

#### 3.1 Indices and their upper bounds

|     |                         |
|-----|-------------------------|
| $P$ | Number of part types    |
| $W$ | Number of worker types  |
| $M$ | Number of machine types |

|     |                                             |
|-----|---------------------------------------------|
| $C$ | Number of cells                             |
| $I$ | Index for part type ( $i=1,2,\dots,P$ )     |
| $W$ | Index for worker ( $w=1, 2,\dots,W$ )       |
| $M$ | Index for machine type ( $m=1, 2,\dots,M$ ) |
| $K$ | Index for cell ( $k=1,2,\dots,C$ )          |

### 3.2 Input parameters

|                 |                                                                                   |
|-----------------|-----------------------------------------------------------------------------------|
| $r_{imw}$       | 1 if machine type $m$ is able to process part $i$ with worker $w$ ; = 0 otherwise |
| $a_{im}$        | 1 if part $i$ needs machine type $m$ ; = 0 otherwise                              |
| $LM_k$          | Minimum size of cell $k$ in terms of the number of machine types                  |
| $LP_k$          | Minimum size of cell $k$ in terms of the number of parts                          |
| $LW_k$          | Minimum size of cell $k$ in terms of the number of workers                        |
| $RW_w$          | Available time for worker $w$                                                     |
| $RM_m$          | Available time for machine $m$                                                    |
| $t_{imw}$       | Processing time of part $i$ on machine type $m$ with worker $w$                   |
| $D_i$           | Demand of part $i$                                                                |
| $\varepsilon_i$ | Unit backorder cost of part $i$                                                   |
| $\alpha_i$      | Unit cost of intercell movement                                                   |
| $A$             | An arbitrary big positive number                                                  |

### 3.3 Decision Variables

|            |                                                                                            |
|------------|--------------------------------------------------------------------------------------------|
| $x_{mk}$   | 1 if machine type $m$ is assigned for cell $k$ ; =0 otherwise                              |
| $y_{ik}$   | 1 if part $i$ is assigned to cell $k$ ; =0 otherwise                                       |
| $z_{wk}$   | 1 if worker $w$ is assigned for cell $k$ ; =0 otherwise                                    |
| $d_{imwk}$ | 1 if part $i$ is to be processed on machine type $m$ with worker $w$ in cell; =0 otherwise |
| $P_i$      | Number of part $i$ to be produced                                                          |

### 3.4 Mathematical formulation

#### 3.4.1 Objective functions

$$\begin{aligned}
 \text{Min} &= \sum_{i=1}^P \alpha_i P_i + \sum_{k=1}^C \sum_{m=1}^M \sum_{w=1}^W [y_{ik} x_{mk} (1 - z_{wk}) d_{imwk}] & (5.1) \\
 &+ \sum_{k=1}^C \sum_{m=1}^M \sum_{w=1}^W [2 \times x_{mk} (1 - y_{ik}) (1 - z_{wk}) d_{imwk}] & (5.2) \\
 &+ \sum_{k=1}^C \sum_{m=1}^M \sum_{w=1}^W [x_{mk} (1 - y_{ik}) z_{wk} d_{imwk}] & (5.3) \\
 &+ \sum_{i=1}^P \varepsilon_i [D_i - P_i] & (5.4)
 \end{aligned}$$

### 3.4.2 Constraints

$$\sum_{k=1}^C \sum_{m=1}^M \sum_{i=1}^P d_{imwk} t_{imw} P_i \leq RW_w \quad \forall w; \quad (6)$$

$$\sum_{w=1}^W \sum_{i=1}^P d_{imwk} t_{imw} P_i \leq RM_m \quad \forall m, k; \quad (7)$$

$$D_i \geq P_i \quad \forall i; \quad (8)$$

$$d_{imwk} \leq r_{imw} x_{mk} \quad \forall i, m, w, k; \quad (9)$$

$$\sum_{k=1}^C \sum_{w=1}^W d_{imwk} = a_{im} \quad \forall i, m; \quad (10)$$

$$\sum_{k=1}^C y_{ik} = 1 \quad \forall i; \quad (11)$$

$$\sum_{i=1}^P y_{ik} \geq LP_K \quad \forall k; \quad (12)$$

$$\sum_{k=1}^C x_{mk} = 1 \quad \forall m; \quad (13)$$

$$\sum_{m=1}^M x_{mk} \geq LM_k \quad \forall k; \quad (14)$$

$$\sum_{k=1}^C z_{wk} = 1 \quad \forall w; \quad (15)$$

$$\sum_{w=1}^W z_{wk} \geq LW_k \quad \forall k; \quad (16)$$

$$x_{mk}, y_{ik}, z_{wk}, d_{imwk} \in \{0, 1\} \quad \forall i, m, w, k; \quad (17)$$

$$P_i \geq 0 \quad \forall i; \quad (18)$$

The objective function consists of several costs items as follows:

**(1), (2), (3) Exceptional Elements:** The first, second and third terms is to minimize the total number of exceptional elements in machine-part-worker incidence matrix. The numbers of exceptional elements for parts are calculated based on the status of availability of corresponding machine and worker as shown in Table 1. If the corresponding machine and worker both are not in the cell, the number of exceptional elements will take value 1 or 2 depending on the availability of machine and worker in one cell or at different cells, respectively. The equations (5.1)-(5.3) can be simplified as follows:

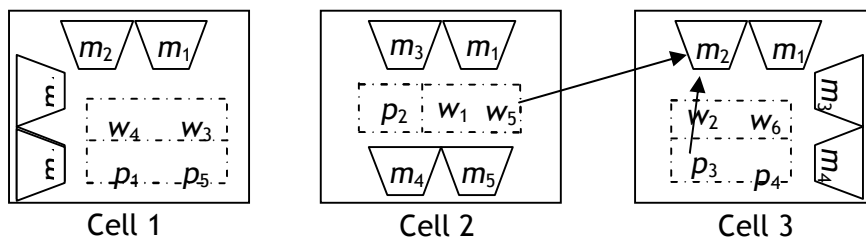
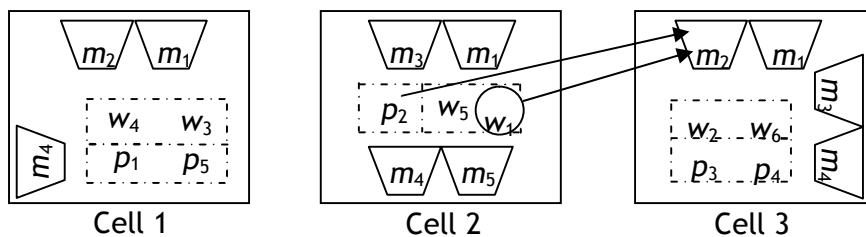
$$\sum_{i=1}^P \sum_{k=1}^C \sum_{m=1}^M \sum_{w=1}^W [x_{mk} (2 - y_{ik} - z_{wk}) d_{imwk}]$$

**Table 1** Status of exceptional elements

| Case | Part | Machine | Worker | Exceptional Elements |
|------|------|---------|--------|----------------------|
| 1    | ✓    | ✓       | ✓      | 0                    |
| 2    | ✓    | ✓       | ×      | 1                    |
| 3    | ×    | ✓       | ×      | 2                    |
| 4    | ×    | ✓       | ✓      | 1                    |

Note: '✓' denotes included and '×' excluded.

To clarify the calculation of exceptional elements, this concept is discussed in Figures 1, 3 and 4. In Figure 1, part type 3 needs worker 5 to get processed on machine type 2. However, part type 3 and machine type 2 have been assigned to cell 3 while worker 5 is in cell 2. Thus, worker 5 has to come to cell 3 which implies one intercellular movement (case 2 of Table 1).

**Fig. 1** Exceptional element for case 2 in Table 1**Fig. 2** Exceptional element for case 3 in Table 1

In Figure 2, let us discuss case 3 of Table 1. In this figure, suppose machine type 2 and worker 1 are required to process part type 2. Furthermore, part type 2, machine type 2 and worker 1 have been assigned to cell 2, cells 1 and 3, and cell 2, respectively. Since part type 2 and worker 1 have to move to cell 3, the number of exceptional elements will be 2.



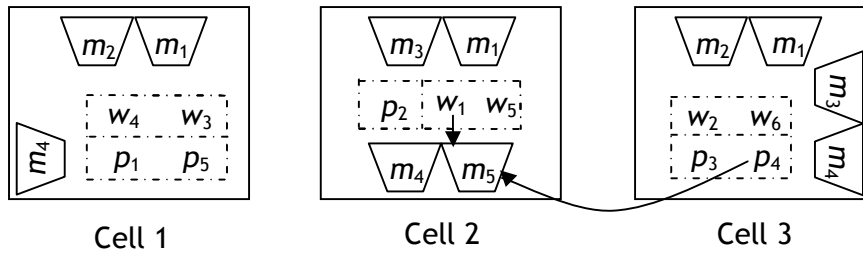


Fig. 3 Exceptional element for case 4 in Table 1

Case 4 of Table 1 is demonstrated in Figure 3. In this figure, suppose machine type 5 and worker 1 are required to process part type 4. Furthermore, suppose part type 4 has been assigned to cell 3 while machine type 5 and worker 1 are in cell 2. Therefore, part type 4 has to move to cell 2 which results in one intercellular movement in this case.

(4) **Backorder cost:** The cost of delay in delivery of all parts. This item is calculated the number of demand for each part, minus the number of production for each part, multiply by the unit backorder cost each part.

### 3.5 Description of constraints

Constraints (6) and (7) ensure that the available time for workers and capacity of machines are not exceeded. Constraint (8) the number of production for each part smaller than the number of demand for each part. Constraint (9) ensures that when machine type  $m$  is not in cell  $k$ , then  $d_{imwk}=0$ . Equation (10) implies that only one worker is allotted for processing each part type on each machine type in one cell. This model is flexible for doing same job with different workers. This means that if one part type is required to be processed by one machine type; more than one worker would be able to service this machine type. Equation (11) ensures that each part type is assigned to only one cell. Constraint (12) forces the lower bound for the number of parts to be allocated to each cell. Equation (13) guarantees that each machine type is assigned to only one cell. Constraint (14) prevents from assigning less than  $LM_k$  machines to cell  $k$ . Equation (15) guarantees that each worker will be assigned to only one cell. Constraint (16) ensures that at least  $LW_k$  workers will be assigned to cell  $k$  in each period;

### 3.6 Linearization of the proposed model

In this section, an attempt is made to linearize the objective function of the mathematical model proposed in Section 3.4.

#### Procedure

The linearization procedure that we propose here consists of two steps that are given by the two lemmas stated below. The non-linear terms in the objective function and constraints (6), (7) are multiplication of binary and integer variables which can be linearized using the following auxiliary integer variables  $E_{imwk}$ ,  $F_{imwk}$ ,  $S_{imwk}$ , and  $G_{imwk}$ . Each lemma for linearization is followed by a proof that illustrates the meaning of each auxiliary (linearization) variable and the expressions where they are used.

**Lemma1.** The non-linear terms in the objective function and constraints (6) and (7) of the mathematical model can be linearized with  $E_{imwk} = P_i \cdot d_{imwk}$ , and  $F_{imwk} = y_{mk} \cdot E_{imwk}$  and  $S_{imwk} = z_{wk} \cdot E_{imwk}$  under the following sets of constraints:

$$E_{imwk} \leq P_i + A(1 - d_{imwk}) \quad \forall i, m, w, k; \quad (19.1)$$

$$E_{imwk} \geq P_i - A(1 - d_{imwk}) \quad \forall i, m, w, k; \quad (19.2)$$

$$E_{imwk} \leq A \cdot d_{imwk} \quad \forall i, m, w, k; \quad (19.3)$$

and

$$F_{imwk} \leq E_{imwk} + A(1 - y_{mk}) \quad \forall i, m, w, k; \quad (19.4)$$

$$F_{imwk} \geq E_{imwk} - A(1 - y_{mk}) \quad \forall i, m, w, k; \quad (19.5)$$

$$F_{imwk} \leq A \cdot y_{mk} \quad \forall i, m, w, k; \quad (19.6)$$

and

$$S_{imwk} \leq E_{imwk} + A(1 - z_{wk}) \quad \forall i, m, w, k; \quad (19.7)$$

$$S_{imwk} \geq E_{imwk} - A(1 - z_{wk}) \quad \forall i, m, w, k; \quad (19.8)$$

$$S_{imwk} \leq A \cdot z_{wk} \quad \forall i, m, w, k; \quad (19.9)$$

**Proof.** This can be shown for each of the two possible cases that can arise.

$$(i) \quad d_{imwk} \cdot P_i = P_i. \quad \forall i, m, w, k;$$

Such a situation arises when  $d_{imwk} = 1$  so, constraints (19.1) and (19.2) implies  $E_{imwk} \leq P_i$  and  $E_{imwk} \geq P_i$  and ensures that  $E_{imwk} = P_i$ .

(ii)  $d_{imwk} \cdot P_i = 0$ . Such a situation arises under one of the following three sub-cases:

$$(a) \quad d_{imwk} = 1 \text{ and } P_i = 0. \quad \forall i, m, w, k;$$

$$(b) \quad d_{imwk} = 0 \text{ and } P_i > 0. \quad \forall i, m, w, k;$$

$$(c) \quad d_{imwk} = 0 \text{ and } P_i = 0. \quad \forall i, m, w, k;$$

In all of the three sub-cases given above,  $E_{imwk}$  takes the value of 0, because in these cases, constraint (19.3) implies  $E_{imwk} \leq 0$  and ensures that  $E_{imwk} = 0$ . Because  $E_{imwk}$  has not a strictly positive cost coefficient, the minimizing objective function doesn't ensures that  $E_{imwk} = 0$ . Thus, constraint (19.3) should be added to the mathematical model.

The performance of constraints (19.4) - (19.9) is similar to constraints' (19.1) and (19.3).

**Lemma2.** The non-linear terms in the objective function can be linearized with  $G_{imwk} = x_{ik} \cdot E_{imwk}$ , under the following set of constraints:

$$G_{imwk} \geq E_{imwk} - A(1 - x_{ik}) \quad \forall i, m, w, k; \quad (20)$$

**Proof.** Consider the following two cases:

(i)  $x_{ik} \cdot E_{imwk} = 0$ . Such a situation arises under one of the following three sub-cases:

(a)  $x_{ik} = 1$  and  $E_{imwk} = 0$ .  $\forall i, m, w, k$ ;

(b)  $x_{ik} = 0$  and  $E_{imwk} > 0$ .  $\forall i, m, w, k$ ;

(c)  $x_{ik} = 0$  and  $E_{imwk} = 0$ .  $\forall i, m, w, k$ ;

In all of the three sub-cases given above, the value of  $G_{imwk} = 0$ , because in these cases, constraint (20) implies  $G_{imwk} \geq 0$  or  $-\infty$  and since  $G_{imwk}$  has a strictly positive cost coefficient, the minimizing objective function ensures that  $G_{imwk} = 0$ .

(ii)  $x_{ik} \cdot E_{imwk} = E_{imwk} > 0$ .  $\forall i, j$ ;

Such a situation arises when  $x_{ik} = 1$  and  $E_{imwk} > 0$  so, constraint (20) implies  $G_{imwk} \geq E_{imwk}$  and since  $G_{imwk}$  has a strictly positive cost coefficient, the minimizing objective function ensures that  $G_{imwk} = E_{imwk}$ .

### 3.6.1 The linearized model

The new version of the first, second and third terms of objective function based on new variables, the linear mathematical model becomes as follows:

$$\begin{aligned} \text{Min} = & \sum_{i=1}^P \sum_{k=1}^C \sum_{m=1}^M \sum_{w=1}^W \alpha_i [2 \times G_{imwk} - F_{imwk} - S_{imwk}] \\ & E_{imwk}, F_{imwk}, G_{imwk}, S_{imwk} \geq 0 \quad \forall i, m, w, k; \end{aligned} \quad (21)$$

Subject to constraints (8) – (21) and new version of constraints (6) and (7):

$$\sum_{k=1}^C \sum_{m=1}^M \sum_{i=1}^P E_{imwk} t_{imw} \leq RW_w \quad \forall w; \quad (22)$$

$$\sum_{w=1}^W \sum_{i=1}^P E_{imwk} t_{imw} \leq RM_m \quad \forall m, k; \quad (23)$$

## 4 Using data envelopment analysis in the CMS model

### 4.1 Choosing the inputs and outputs for DEA model

Manned cells are a very flexible system that can adapt to changes in the customers demand or changes quite easily and rapidly in the product design. The cells described in this study are designed for flexibility. In this study, the DEA is applied to the problem of comparing and evaluating the alternative rescoring assignment in a CMS environment. In general, in a number of previous DEA evaluation models, the criteria that are to be minimized are viewed as inputs, and the criteria to be maximized are considered as outputs (Doyle and Green [36]). In other words, usually the DEA assumes that outputs are increasing and more of an output is better than less of the output. Alternatives consisted of reducing the number of machines, the

number of workers, the number of parts and the demand of each part in the cell is as follows in details:

- Choice 4 machine among 5 machine type that have different availability level the DM have 4 alternatives to choice machines 1, 2, 3, 4 (alternative A), 1, 2, 3, 5 (B), 1, 2, 4, 5 (C), 1, 3, 4, 5 (D).
- Use 3 worker in the cell that the workers number 1 and number 2 have the same level and the workers number 3 and number 4 have the same level, since the DM have 2 alternative for choose the workers, worker 1, worker 2 and worker 3 (F), worker 2, worker 3 and worker 4 (G).
- The number of parts type for produce is 4 or 5. The production value (backorder cost) all of the parts are the same level so DM have 2 alternatives to choice parts.
- Numbers of demand for each part are 300 and 350, and DM have 2 alternatives to choice volume of the parts.

So DM have  $4 \times 2 \times 2 \times 2 = 32$  alternatives to decision.

To illustrate the capability of the proposed model an alternative have been solved by branch and bound (B&B) method under Lingo 9.0 software package.

In all alternatives we consider two cells with different machines, parts and workers. The data set related to the all alternatives are shown in Tables 2 and 3. Table 2 indicates machines requirement of parts. For example, part type 3 requires machine types 2 and 4. Table 3 indicates capabilities of workers in working with different machines. For example, worker 3 is able to work with machine types 2 and 4. The available time of worker in each period is 20 hours and the available time of machine in each period is 20 hours. Also the processing time is presented in Table 4. Moreover, backorder cost per unit each part types are 1. The number of batch size each part is 100. Also, the minimum size of each cell in terms of the number of machines, parts and workers has been considered to value one.

**Table 2** The input data of machine-part incidence matrix

|       | Machines |   |   |   |   |
|-------|----------|---|---|---|---|
|       | 1        | 2 | 3 | 4 | 5 |
|       | 1        | 1 | 1 | 1 | 1 |
|       | 2        | 1 | 0 | 1 | 0 |
|       | 3        | 0 | 1 | 0 | 1 |
|       | 4        | 0 | 1 | 0 | 1 |
| Parts | 5        | 1 | 0 | 1 | 0 |

**Table 3** The input data of machine-worker incidence matrix

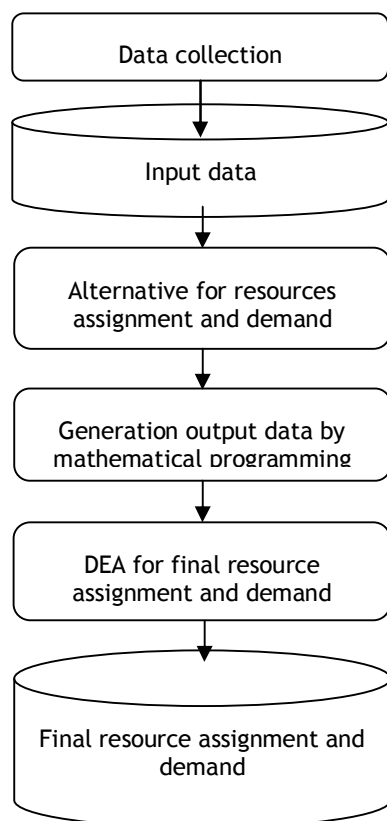
|          | Workers |   |   |   |
|----------|---------|---|---|---|
|          | 1       | 2 | 3 | 4 |
|          | 1       | 1 | 0 | 0 |
|          | 2       | 0 | 1 | 1 |
|          | 3       | 1 | 0 | 0 |
|          | 4       | 0 | 1 | 1 |
| Machines | 5       | 1 | 0 | 0 |

**Table 4** The processing time (hrs.)

|    | Part1 |     |     | Part2 |     |    | Part3 |     |     | Part4 |    |    | Part5 |     |     |
|----|-------|-----|-----|-------|-----|----|-------|-----|-----|-------|----|----|-------|-----|-----|
|    | W1    | W2  | W3  | W4    | W1  | W2 | W3    | W4  | W1  | W2    | W3 | W4 | W1    | W2  | W3  |
| M1 | .02   |     |     | .02   | .02 |    |       | .02 |     |       |    |    | .02   |     | .02 |
| M2 |       | .04 | .04 |       |     |    |       |     | .04 | .04   |    |    | .04   | .04 |     |
| M3 | .03   |     |     | .03   | .03 |    |       | .03 |     |       |    |    | .03   |     | .03 |
| M4 |       | .01 | .01 |       |     |    |       |     | .01 | .01   |    |    | .01   | .01 |     |
| M5 | .01   |     |     | .01   | .01 |    |       | .01 |     |       |    |    | .01   |     | .01 |

Table 5 shows the results of alternative 1. It indicates the assignment of parts, machines and workers in cells. For instance, workers 3 and 4 are assigned in cell 1, and worker 1 and 2 is assigned in cell 2. Also machine type 2 is assigned in cell 1 and machines 1, 3 and 4 are assigned in cell 2. Moreover, it shows the allotment of worker for each part, in cell for work on corresponding machine. For instance, part 3 shall process with machine 2 (see Table 4) and workers 2 and 3 capability of working to this machine (see Table 5) which this operation is executed by worker 3 in cell 1 (see Table 5).

The volume of products and objective function value including backorder cost and number of exceptional elements (EEs) has been indicated in Table 5. As can be seen, the demand of part 2 in is 350 but this part is 316 produced. This means, the 34 volume of demand of part 2 is which causes backorder cost.



**Fig. 4** Steps of the proposed methodology

These alternatives inputs data of the mathematical model are indicated in the Table 6. Steps of the proposed methodology are presented in Fig. 4.

**Table 5** The result of alternative 1

| Backorder cost    |       |         |         | EEs |   |   |   | Part 1  | Part 2 | Part 3 | Part 4 | Part 5         |   |   |   |                |   |   |   |   |  |  |  |
|-------------------|-------|---------|---------|-----|---|---|---|---------|--------|--------|--------|----------------|---|---|---|----------------|---|---|---|---|--|--|--|
| 584               |       |         |         | 14  |   |   |   | Workers |        |        |        |                |   |   |   |                |   |   |   |   |  |  |  |
|                   | Cell1 | Cell2   | Machine | 1   | 2 | 3 | 4 | 1       | 2      | 3      | 4      | 1              | 2 | 3 | 4 | 1              | 2 | 3 | 4 |   |  |  |  |
| Part              | 1     | 2,3,4,5 | 1       |     |   |   |   | 2       |        |        |        | 1 <sup>b</sup> |   |   |   | 1 <sup>b</sup> |   |   |   | 2 |  |  |  |
| Machine           | 2     | 1,3,4   | 2       |     |   |   |   |         |        |        |        |                |   |   |   |                |   |   |   |   |  |  |  |
| Worker            | 3,4   | 1,2     | 3       |     |   |   |   |         |        |        |        |                |   |   |   |                |   |   |   |   |  |  |  |
|                   |       |         | 4       |     |   |   |   |         |        |        |        |                |   |   |   |                |   |   |   |   |  |  |  |
| Volume of Product |       |         |         | 0   |   |   |   | 316     |        |        |        | 150            |   |   |   | 350            |   |   |   |   |  |  |  |

<sup>a</sup> The worker movement between cells

<sup>b</sup> The part movement between cells

For each alternative we use the developed CMS and calculate average machine utilization (ATUM) and average worker utilization (ATUW) and mean of product from the solutions and set them as the alternative results data of the mathematical model, Table 9 shows the results of 60 alternatives.

**Table 6** The inputs of the DEA model

| DMU | Number of machines | Number of worker | Number of parts | Demand level | DMU | Number of machines | Number of workers | Number of parts | Demand level |
|-----|--------------------|------------------|-----------------|--------------|-----|--------------------|-------------------|-----------------|--------------|
| 1   | 4(A)               | 4                | 5               | 350          | 31  | 4(C)               | 3(F)              | 4               | 350          |
| 2   | 4(A)               | 4                | 5               | 300          | 32  | 4(C)               | 3(F)              | 4               | 300          |
| 3   | 4(A)               | 4                | 4               | 350          | 33  | 4(C)               | 3(G)              | 5               | 350          |
| 4   | 4(A)               | 4                | 4               | 300          | 34  | 4(C)               | 3(G)              | 5               | 300          |
| 5   | 4(A)               | 3(F)             | 5               | 350          | 35  | 4(C)               | 3(G)              | 4               | 350          |
| 6   | 4(A)               | 3(F)             | 5               | 300          | 36  | 4(C)               | 3(G)              | 4               | 300          |
| 7   | 4(A)               | 3(F)             | 4               | 350          | 37  | 4(D)               | 4                 | 5               | 350          |
| 8   | 4(A)               | 3(F)             | 4               | 300          | 38  | 4(D)               | 4                 | 5               | 300          |
| 9   | 4(A)               | 3(G)             | 5               | 350          | 39  | 4(D)               | 4                 | 4               | 350          |
| 10  | 4(A)               | 3(G)             | 5               | 300          | 40  | 4(D)               | 4                 | 4               | 300          |
| 11  | 4(A)               | 3(G)             | 4               | 350          | 41  | 4(D)               | 3(F)              | 5               | 350          |
| 12  | 4(A)               | 3(G)             | 4               | 300          | 42  | 4(D)               | 3(F)              | 5               | 300          |
| 13  | 4(B)               | 4                | 5               | 350          | 43  | 4(D)               | 3(F)              | 4               | 350          |
| 14  | 4(B)               | 4                | 5               | 300          | 44  | 4(D)               | 3(F)              | 4               | 300          |
| 15  | 4(B)               | 4                | 4               | 350          | 45  | 4(D)               | 3(G)              | 5               | 350          |
| 16  | 4(B)               | 4                | 4               | 300          | 46  | 4(D)               | 3(G)              | 5               | 300          |
| 17  | 4(B)               | 3(F)             | 5               | 350          | 47  | 4(D)               | 3(G)              | 4               | 350          |
| 18  | 4(B)               | 3(F)             | 5               | 300          | 48  | 4(D)               | 3(G)              | 4               | 300          |
| 19  | 4(B)               | 3(F)             | 4               | 350          | 49  | 4(E)               | 4                 | 5               | 350          |
| 20  | 4(B)               | 3(F)             | 4               | 300          | 50  | 4(E)               | 4                 | 5               | 300          |
| 21  | 4(B)               | 3(G)             | 5               | 350          | 51  | 4(E)               | 4                 | 4               | 350          |
| 22  | 4(B)               | 3(G)             | 5               | 300          | 52  | 4(E)               | 4                 | 4               | 300          |
| 23  | 4(B)               | 3(G)             | 4               | 350          | 53  | 4(E)               | 3(F)              | 5               | 350          |
| 24  | 4(B)               | 3(G)             | 4               | 300          | 54  | 4(E)               | 3(F)              | 5               | 300          |
| 25  | 4(C)               | 4                | 5               | 350          | 55  | 4(E)               | 3(F)              | 4               | 350          |
| 26  | 4(C)               | 4                | 5               | 300          | 56  | 4(E)               | 3(F)              | 4               | 300          |
| 27  | 4(C)               | 4                | 4               | 350          | 57  | 4(E)               | 3(G)              | 5               | 350          |
| 28  | 4(C)               | 4                | 4               | 300          | 58  | 4(E)               | 3(G)              | 5               | 300          |
| 29  | 4(C)               | 3(F)             | 5               | 350          | 59  | 4(E)               | 3(G)              | 4               | 350          |
| 30  | 4(C)               | 3(F)             | 5               | 300          | 60  | 4(E)               | 3(G)              | 4               | 300          |

**Table 7** The outputs of the DEA model

| DMU | Mean of product(%) | ATUM(%) | ATUW(%) | DMU | Mean of product(%) | ATUM(%) | ATUW(%) |
|-----|--------------------|---------|---------|-----|--------------------|---------|---------|
| 1   | 66.5               | 72.9    | 72      | 31  | 83.1               | 51.4    | 66.3    |
| 2   | 73.3               | 72.9    | 72      | 32  | 91.6               | 53.6    | 75.8    |
| 3   | 83.1               | 72.9    | 72      | 33  | 56                 | 37      | 74.1    |
| 4   | 91.6               | 68.5    | 60      | 34  | 58.3               | 49.2    | 66.3    |
| 5   | 51.4               | 56.9    | 75.8    | 35  | 78.5               | 38.5    | 68.5    |
| 6   | 60                 | 56.9    | 75.8    | 36  | 83.3               | 47      | 63.6    |
| 7   | 64.2               | 56.9    | 75.8    | 37  | 78                 | 59.2    | 59.2    |
| 8   | 75                 | 58.5    | 70      | 38  | 77.3               | 58.5    | 57      |
| 9   | 60.8               | 58.5    | 77.4    | 39  | 97.4               | 58.5    | 58.5    |
| 10  | 66.6               | 62.5    | 83.6    | 40  | 100                | 52.9    | 55.8    |
| 11  | 76                 | 66.3    | 88.5    | 41  | 58.8               | 33.6    | 44.1    |
| 12  | 83.3               | 62.9    | 83.6    | 42  | 84.3               | 58.5    | 77      |
| 13  | 66.2               | 59.2    | 59.2    | 43  | 73.7               | 33.6    | 44.1    |
| 14  | 73.3               | 55.8    | 55.8    | 44  | 77.6               | 26.3    | 43.6    |
| 15  | 83.2               | 74.1    | 74.1    | 45  | 78                 | 47      | 83.6    |
| 16  | 91.6               | 70      | 70      | 46  | 84.3               | 59.2    | 74.1    |
| 17  | 47.6               | 49.2    | 66.3    | 47  | 97.4               | 58.5    | 78.5    |
| 18  | 55.5               | 49.2    | 66.3    | 48  | 100                | 52.9    | 70      |
| 19  | 59.4               | 49.2    | 66.3    | 49  | 66.5               | 54.1    | 64.1    |
| 20  | 69.4               | 49.2    | 66.3    | 50  | 73.2               | 64.1    | 64.1    |
| 21  | 67.7               | 74.1    | 99.2    | 51  | 83.2               | 64.1    | 64.1    |
| 22  | 73.3               | 70      | 93.6    | 52  | 91.6               | 61.4    | 58.5    |
| 23  | 83.2               | 74.1    | 99.2    | 53  | 56.5               | 55.8    | 74.1    |

| DMU | Mean of product(%) | ATUM(%) | ATUW(%) | DMU | Mean of product(%) | ATUM(%) | ATUW(%) |
|-----|--------------------|---------|---------|-----|--------------------|---------|---------|
| 24  | 91.6               | 70      | 93.6    | 54  | 66.6               | 56.3    | 75.8    |
| 25  | 68.5               | 53.6    | 44.3    | 55  | 71.4               | 56.3    | 75.8    |
| 26  | 73.3               | 65.8    | 65.8    | 56  | 83.3               | 51.4    | 75.8    |
| 27  | 85.7               | 57      | 57      | 57  | 60.8               | 58.5    | 77      |
| 28  | 91.6               | 64.1    | 56.3    | 58  | 66.6               | 55.8    | 73.6    |
| 29  | 66.5               | 56.3    | 74.1    | 59  | 76.8               | 54.1    | 77      |
| 30  | 73.3               | 49.2    | 71.4    | 60  | 83.3               | 55.8    | 73.6    |

#### 4.2. The most efficient alternative

We used the model 2 for 60 inputs and outputs shown in the Tables 6 and 7, The DEA is applied to the data set of 60  $DMU_s$ . The efficiency scores obtained using DEA are listed in Table 8. The DEA results denote that 9 cases of 60  $DMU_s$  are relatively efficient; however, a ranking cannot be obtained for these  $DMU_s$ . Since the efficiencies evaluate 9 of the 60  $DMU_s$  as efficient and cannot discriminate among them any further, a ranking method is needed. We are use the  $L_\infty$ -norm model 6 to rank these 9 alternatives. The results are shown in Table 9. According to the  $L_\infty$ -norm method in Table 9, DMU24 is the most efficient alternative, whereas DMU48 is the second most efficient followed by DMU23, DMU47 and others.

**Table 8** Efficiency scores that are obtained by DEA

| DMU | Efficiency score | DMU | Efficiency score | DMU | Efficiency score | DMU | Efficiency score |
|-----|------------------|-----|------------------|-----|------------------|-----|------------------|
| 1   | 0.9838           | 16  | 1.0000           | 31  | 0.8591           | 46  | 0.8999           |
| 2   | 0.9836           | 17  | 0.6683           | 32  | 0.9493           | 47  | 1.0000           |
| 3   | 0.9891           | 18  | 0.7083           | 33  | 0.7470           | 48  | 1.0000           |
| 4   | 0.9906           | 19  | 0.6847           | 34  | 0.7083           | 49  | 0.8650           |
| 5   | 0.7679           | 20  | 0.7445           | 35  | 0.8217           | 50  | 0.8702           |
| 6   | 0.8129           | 21  | 1.0000           | 36  | 0.8481           | 51  | 0.9128           |
| 7   | 0.7692           | 22  | 0.9446           | 37  | 0.8489           | 52  | 0.9466           |
| 8   | 0.8357           | 23  | 1.0000           | 38  | 0.8403           | 53  | 0.7530           |
| 9   | 0.7895           | 24  | 1.0000           | 39  | 0.9874           | 54  | 0.7771           |
| 10  | 0.8932           | 25  | 0.7587           | 40  | 1.0000           | 55  | 0.7978           |
| 11  | 0.9014           | 26  | 0.8879           | 41  | 0.5973           | 56  | 0.8813           |
| 12  | 0.9051           | 27  | 0.8862           | 42  | 0.8972           | 57  | 0.7894           |
| 13  | 0.7989           | 28  | 1.0000           | 43  | 0.7370           | 58  | 0.7698           |
| 14  | 0.7988           | 29  | 0.7738           | 44  | 0.7760           | 59  | 0.8339           |
| 15  | 1.0000           | 30  | 0.7902           | 45  | 0.8767           | 60  | 0.8772           |

**Table 9** The Tchebycheff values and Ranking efficient DMUs DEA

| DMU | Tch. norm   |      | DMU | Tch. norm   |      | DMU | Tch. Norm   |      |
|-----|-------------|------|-----|-------------|------|-----|-------------|------|
|     | Value       | Rank |     | Value       | Rank |     | Value       | Rank |
| 15  | 1.8855e-009 | 5    | 23  | 0.2295      | 3    | 40  | 7.2731e-015 | 8    |
| 16  | 8.0071e-010 | 7    | 24  | 6.7066      | 1    | 47  | 0.0131      | 4    |
| 21  | 1.4388e-009 | 6    | 28  | 3.4715e-017 | 9    | 48  | 1.9761      | 2    |

## 5 Conclusions

In this paper, a neutral DEA in CMS is proposed for a three-dimensional machine-part-worker incidence matrix which demonstrates a cubic representation of assignment in cellular manufacturing system. Moreover, the new concept of exceptional elements is discussed to

show the interpretation of inter-cell movements of both workers and parts for processing on corresponding machines. The proposed approach minimizes backorder cost and intercellular cost in a cellular manufacturing system. The DEA approach performed for determining the most efficient alternative among 60 alternatives that considered. As a result of the application of classic DEA model, 9 alternatives are determined as relatively efficient. To increase discriminating power among alternatives and ranking, the tchebycheff-norm ranking method was employed.

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