

# Design of Cellular Manufacturing Systems Considering Dynamic Production Planning and Worker Assignments

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**Abstract:** This article presents a comprehensive mathematical model for the design and analysis of Dynamic Cellular Manufacturing Systems (DCMS). The proposed DCMS model considers several manufacturing attributes such as multi period production planning, dynamic system reconfiguration, duplicate machines, machine capacity, the available time for workers, worker assignments, and machine procurement. The objective is to minimize total costs; consisting of holding cost, outsourcing cost, inter-cell material handling cost, maintenance and overhead cost, machine relocation cost. While a study of published articles in the area of Cellular Manufacturing Systems (CMS) shows that workforce management issues have not sufficiently been addressed in the literature, the model presented also incorporates CMS workforce management issues such as salaries, hiring and firing costs of workers in addition to the manufacturing attributes. In-depth discussions on the results for two numerical examples are presented to illustrate applications of the proposed model. The model developed aims to raise the envelope by expanding and improving several CMS models previously presented in the literature.

**Keywords:** Facilities planning and design, Cellular Manufacturing Systems, Mixed Integer Programming, Production Planning, Worker Assignments.

## 1. Introduction

Manufacturing facility layout designs depend on a number of factors including the demand volumes as well as the product variety. Nowadays, due to the international competition, shorter product life-cycles, variable demand, diverse customer needs, and customized products, manufacturers are forced from mass production to the production of a large product mix. Cellular Manufacturing (CM) presents good performance in satisfying the demand of mid-volume and mid-variety products mixed rather than job shops or flow lines. CM is an application of group technology in manufacturing in which similar parts are classified into part families and different machines are assigned into machine cells [2]. There are many

benefits of cellular manufacturing for a manufacturing facility, if applied correctly. Processes become more balanced and productivity increases. Part movements, set-up times, and waiting times between operations are reduced, resulting in a reduction of work-in-process inventory freeing idle capital that can be better utilized elsewhere. Cellular manufacturing, in combination with the other lean manufacturing and just-in-time processes, also helps to eliminate overproduction by producing items only when they are needed. The results are cost savings and a better control of operations [1].

In this paper, a comprehensive Dynamic Cellular Manufacturing System (DCMS) model is presented. The proposed DCMS model considers several manufacturing attributes such as multi period production planning, dynamic system reconfiguration, duplicate machines, machine capacity, the available

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time for workers, worker assignments, and machine procurement. The objective is to minimize total costs; consisting of holding cost, outsourcing cost, inter-cell material handling cost, maintenance and overhead cost, machine relocation cost, as well as salaries, and hiring and firing cost of workers. The model developed aims to raise the envelope by expanding and improving several CMS models previously presented in the literature.

The remainder of this article is organized as follows. Section 2 presents a review of the relevant literature. The mathematical model developed, its assumptions as well as the model description are presented in section 3. In-depth discussions on the results of two examples are presented in section 4. Section 5 presents the conclusions and the future research.

## 2. Literature Review

Comprehensive summaries and taxonomies of studies devoted to cell formation problem have been presented by [8-11]. Many authors proposed models, which consider dynamic cell reconfiguration over multi periods [1-6].

While the main emphasis of the previously published works on CMS have been on the technical aspects (e.g. cell formation and design), with the exception of a handful of articles, workforce management aspects in cellular manufacturing (e.g. worker assignments, hiring and firing costs) have been overlooked in the literature. Ignoring the “*human element*” in the CMS design methodologies will reduce the reliability, and hence, the benefits of the proposed models expected from their implementation. The following articles approach Cellular Manufacturing Systems from a workforce management perspective:

Nembhard [11] presented a heuristic worker-task assignment based on individual worker learning rates to improve organizations’ productivity. Gel et al. [16] introduced in their study the factors that are affecting the work sharing amongst the workers as a dynamic line balancing mechanism. In order to maximize the

effectiveness of the organization, Norman et al. [20] developed a mixed integer programming model for worker assignment in manufacturing cells with the ability of worker training in order to change their skill levels. Sennott et al. [18] studied the worker flexibility assignment in an open production line with specialists by formulating Markov decision process models of K-station production lines. Hopp and Oyen [17] presented approaches for assessing and classifying manufacturing and service operations in terms of their suitability for use of cross-trained workers. Bidanda et al. [12] presented a survey to determine the importance of eight different human issues in cellular manufacturing. The results of the survey were presented and discussed. Based on the type of machine-operator assignments Cesani and Steudel [21] classified the labor allocation strategies into three main categories; dedicated, shared, and combined assignments. By using simulation modelling, they studied the impact of these strategies on the system performance. Wirojanagud et al. [22] claimed that workers are inherently different, they developed a model which considered differences in workers’ cognitive abilities and to give answers to when, where, and whom to hire, cross-train, or fire, and to indicate the optimal amount of missed production. Part routing flexibility, machine flexibility, and workers with different skill levels proposed by Aryanezhad et al. [7]. Mahdavi et al. [19] developed an integer non-linear mathematical programming model and followed some linearization steps in order to obtain an integer linear problem and solved two examples. Their model includes relevant aspects such as multi-period production planning, dynamic system reconfiguration, duplicate machines, machine capacity, available time of workers, and worker assignments. Although the Mahdavi et al. [19] model is well-integrated, it does not take into consideration certain issues that are addressed in this paper; such as machine procurement cost, internal part production cost, machine operating cost, and outsourcing cost. Rafiei and Dehgan [15]

considered labor flexibility, workload sharing, and workload balancing to build a procedure for labor assignment in cellular manufacturing. Nikkfarid and Aalaei [14] presented a mathematical model for designing a dynamic virtual cellular manufacturing system (DVCMS), which incorporates many important manufacturing attributes. Liu et al. [13] focused on training and assignment problem of multi-skilled workers. An investigation on how to obtain the task-to-worker training and worker-to-seru (i.e. Seru production system is a new type of work-cell based manufacturing system. In implementing the seru production, the multi-skilled worker is the most important precondition) assignment plans when the differences of training cost and processing time of each task for different workers are considered simultaneously. The model developed in this article covers a larger number of manufacturing attributes that are important in CMS design and integrate more of these attributes in comparison with those previously reported in the literature.

### 3. Description of the Problem and of the Mathematical Model

In this section, we present a formal description of the proposed mathematical model and its assumptions

#### 3.1 Model Assumptions

- The demand for each part type in each period is known and deterministic.
- Each machine type has a limited capacity expressed in hours during each time period.
- Reconfiguration involves the addition and removal of machines to any cell and relocation from one cell to another between periods. It also involves the addition and removal of worker to any cell and relocation from one cell to another between periods.
- Maintenance and overhead costs of each machine type are known. These costs are considered for each machine in each cell and period regardless that the machine is active or idle.

- Salary of each worker type is known. This cost is considered for each worker in each cell and period no matter that the worker is active or idle.
- The available time for each worker is known.
- The number of cells is known and constant during all periods.
- Only one worker is allotted for processing each part on each corresponding machine.
- The demand for each part in each period can be satisfied by production, inventory from the last periods and/or, purchasing.

#### 3.2 Model Description

The integrated problem is formulated as an integer nonlinear programming model based on dynamic cellular manufacturing system with worker assignments in this section. The objective function is to minimize machine maintenance and overhead cost, intercell travel cost, part holding cost, outsourcing cost, reconfiguration cost, machine procurement cost, internal production cost, machine operating cost, worker hiring, firing, and salary cost. The notations used for the model are presented followed by the objective function, and constraints.

Sets:

- $p = \{1, 2, 3 \dots P\}$  Index set of part types.
- $m = \{1, 2, 3 \dots M\}$  Index set of machine types.
- $c = \{1, 2, 3 \dots C\}$  Index set of cells.
- $t = \{1, 2, 3 \dots T\}$  Index set of time periods.
- $w = \{1, 2, 3 \dots W\}$  Index set of worker types.

Model Parameters:

- $D_{pt}$  Demand for part type  $p$  in time period  $t$
- $V_p^{inter}$  Intercell movement cost of part type  $p$   
= 1, if machine type  $m$  is able to process part type  $p$   
with worker  $w$ ,  
= 0, otherwise.
- $\mu_{mpw}$  = 1, if part type  $p$  needs machine type  $m$ ,  
= 0, otherwise.
- $\lambda_{pm}$  = 1, if part type  $p$  needs machine type  $m$ ,  
= 0, otherwise.
- $U_p$  Outsourcing cost per unit of part type  $p$  in period  $t$ .
- $t_{pmw}$  Processing time part type  $p$  on machine type  $m$  with worker type  $w$
- $T_{mt}$  Time capacity of one machine of type  $m$  for one time period  $t$

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$LL_c$	Minimum number of machines limit in cell $c$
$UL_c$	Maximum number of machines limit in cell $c$
$LW_c$	Minimum size of cell $c$ in terms of the number of workers
$R_m^+$	Relocation cost of installing one machine of type $m$
$R_m^-$	Relocation cost of removing one machine of type $m$
$L^p$	a large positive number
$H_{pt}$	Part holding cost per part type $p$ per time period $t$
$A_m$	Quantity of machine type $m$ available at time period $t=1$
$A_w$	Number of worker type $w$ available
$RW_{wt}$	Available time for worker type $w$ at time period $t$
$S_{wt}$	Salary cost of worker type $w$ within period $t$
$HI_{wt}$	Hiring cost of worker type $w$ within period $t$
$F_{wt}$	Firing cost of worker type $w$ within period $t$
$OV_m$	Machine maintenance overhead cost of machine type $m$ per unit time in time period $t$
$OP_m$	Procurement cost per machine type $m$
$Y_m$	Operating cost per unit time per machine type $m$
$\xi_p$	Internal production cost per part type $p$

### Model Decisions Variables:

$N_{mct}$	Number of type $m$ machines to present at cell $c$ at beginning of time period $t$
$Y_{mct}^+$	Number of type $m$ machines added in cell $c$ at beginning of time period $t$
$Y_{mct}^-$	Number of type $m$ machines removed from cell $c$ at beginning of time period $t$
$BN_{mt}$	Number of machines of type $m$ procured at time $t$
$A_{mt}^*$	Quantity of machine type $m$ available at time period $t$ after accounting for machines that have been procured
$Q_{pt}$	Number of part inventory of type $p$ kept in time period $t$ and carried over to period $(t+1)$
$\beta_{pt}$	Production volume of part type $p$ to be produced in time period $t$
$O_{pt}$	Number of parts to be outsourced at time period $t$ .
$L_{wct}^+$	Number of workers of type $w$ added to cell $c$ during period $t$
$L_{wct}^-$	Number of workers of type $w$ removed from cell $c$ during period $t$
$N_{wct}$	Number of workers of type $w$ allotted to cell $c$ in period $t$
$v_{pct}$	= 1, if part type $p$ is processed in cell $c$ in period $t$ . = 0, otherwise.
$z_{pmwct}$	= 1, if part type $p$ is to be processed on machine type $m$ with worker $w$ in cell $c$ in period $t$ . = 0, otherwise.

### 3.3 The Integer Programming Model

The objective function and constraints of the model

are as follows:

Minimize

$$\sum_{t=1}^T \sum_{c=1}^C \sum_{m=1}^M N_{mpt} \cdot OV_m \quad (1.1)$$

$$+ \sum_{t=1}^T \sum_{c=1}^C \sum_{m=1}^M R_m^+ \cdot Y_{mk}^+(t) \quad (1.2)$$

$$+ \sum_{t=1}^T \sum_{c=1}^C \sum_{m=1}^M R_m^- \cdot Y_{mk}^-(t) \quad (1.3)$$

$$+ \sum_{t=1}^T \sum_{p=1}^P Q_{pt} \cdot H_{pt} \quad (1.4)$$

$$+ \sum_{t=1}^T \sum_{p=1}^P O_{pt} \cdot U_p \quad (1.5)$$

$$+ \sum_{t=1}^T \sum_{c=1}^C \sum_{w=1}^W S_{wt} \cdot N_{wct} \quad (1.6)$$

$$+ \sum_{t=1}^T \sum_{c=1}^C \sum_{w=1}^W HI_{wt} \cdot L_{wct}^+ \quad (1.7)$$

$$+ \sum_{t=1}^T \sum_{c=1}^C \sum_{w=1}^W F_{wt} \cdot L_{wct}^- \quad (1.8)$$

$$+ \sum_{t=1}^T \sum_{p=1}^P \left[ \left( \sum_{c=1}^C v_{pct} \right) - 1 \right] \cdot V_p^{inter} \cdot \beta_{pt} \quad (1.9)$$

$$+ \sum_{t=1}^T \sum_{m=1}^M BN_{mt} \cdot OP_m \quad (1.10)$$

$$+ \sum_{t=1}^T \sum_{p=1}^P \beta_{pt} \cdot \xi_p \quad (1.11)$$

$$+ \sum_{t=1}^T \sum_{p=1}^P \sum_{m=1}^M \sum_{w=1}^W \sum_{c=1}^C z_{pmwct} * \beta_{pt} * t_{pmw} * Y_m \quad (1.12)$$

Subject to

$$\beta_{pt} + Q_{p(t-1)} - Q_{pt} + O_{pt} = D_{pt}; \forall(p, t) \quad (2)$$

$$v_{pct} = \min(1, \sum_{m=1}^M \sum_{w=1}^W z_{pmwct}); \forall(p, c, t) \quad (3)$$

$$\sum_{c=1}^C z_{pmwct} \leq \mu_{mpw}; \forall(p, m, w, t) \quad (4)$$

$$\sum_{m=1}^M \sum_{w=1}^W z_{pmwct} = \lambda_{pm}; \forall(p, m, t) \quad (5)$$

$$N_{mct} = N_{mc(t-1)} + Y_{mct}^+ - Y_{mct}^-; \forall(m, c, t) \quad (6)$$

$$LB_c \leq \sum_{m=1}^M N_{mct} \leq UB_c; \forall(c, t) \quad (7)$$

$$\sum_{w=1}^W N_{wct} \geq L_{wc}, \forall(c, t) \quad (8)$$

$$\sum_{m=1}^M \sum_{p=1}^P z_{pmwct} \cdot t_{pmw} \cdot \beta_{pt} \leq N_{wct} R W_{wt}, \forall(w, c, t) \quad (9)$$

$$\sum_{w=1}^W \sum_{p=1}^P z_{pmwct} \cdot t_{pmw} \cdot \beta_{pt} \leq N_{mct} \cdot T_{mt}, \forall(m, c, t) \quad (10)$$

$$N_{wct(t-1)} + L_{wct}^+ - L_{wct}^- = N W_{wct}, \forall(w, c, t) \quad (11)$$

$$\sum_{c=1}^C N_{wct} \leq A W_w, \forall(w, t) \quad (12)$$

$$\sum_{c=1}^C \sum_{m=1}^M \sum_{w=1}^W z_{pmwct} \leq \beta_{pt} \cdot L^p; \forall(p, t) \quad (13)$$

$$A_{m(t=1)}^* = A_{m(t=1)} + B N_{m(t=1)}, \forall(m) \quad (14)$$

$$A_{m(t+1)}^* = A_{mt}^* + B N_{m(t+1)}, \forall(m) \quad (15)$$

$$\sum_{c=1}^C N_{mct} \leq A_{mt}^*; \forall(m, t) \quad (16)$$

$$N_{mct}; Y_{mct}^+; Y_{mct}^- \geq 0 \text{ and integer } \forall(m, c, t)$$

$$L_{wct}^+; L_{wct}^-; N_{wct} \geq 0 \text{ and integer } \forall(w, c, t)$$

$$Q_{pt}; \beta_{pt}; O_{pt} \geq 0 \text{ and integer } \forall(p, t) \quad (17)$$

$$B N_{mt}; A_{mt}^* \geq 0 \text{ and integer } \forall(m, t)$$

$$v_{pct} \in \{0, 1\} \forall(p, c, t)$$

$$z_{pmwct} \in \{0, 1\} \forall(p, m, w, c, t)$$

The objective function has several terms. The first term (1.1) represents machines maintenance overhead cost. The second term (1.2) represents relocation cost of machines installation. The third term (1.3) represents relocation cost of machines removal. The fourth term (1.4) represents part holding cost. The fifth term (1.5) represents outsourcing cost. The sixth term (1.6) represents the salary worker cost. Term (1.7) represents the hiring worker cost. Term (1.8) represents the firing worker cost. The ninth term (1.9) represents part intercellular movement cost. Tenth term (1.10) represents machine procurement cost. Term (1.11) represents the internal production cost. Term (1.12) represents machine operating cost.

The objective function is subjected to constraints as

follows: Constraint (2) shows that demand of part type  $p$ , in each time period  $t$  is satisfied through internal part production, and/or part inventory carried over from previous period, and/or outsourcing. Equation (3) is to determine whether part type  $p$  is processed within cell  $c$  in period  $t$ . Constraints (4) and (5) is to make sure that only one worker is assigned for each part on each machine type. Constraint (6) is to ensure that the number of machines type  $m$  in current period is equal to the number of machines in the previous period, adding the number of machines moved in and subtracting the number of machines moved out of the cell  $c$ . By constraint (7), lower and upper bounds on sizes of cell in terms of the number of machines are enforced. Constraint (8) ensures that the minimum number of workers to be assigned to cell  $k$  in each period. Constraints (9) and (10) ensure that the available time for workers and capacity of machines are not exceeded, respectively. Equation (11) balances the number of workers between consecutive time periods. Constraint (12) guarantees that the total number of workers of each type assigned to different cells in each period will not exceed total available number of workers of that type. Constraint (13) ensures that If  $\beta_{pt} = 0$ , no machines, worker and cell should be considered. Constraint (14) relates to the machine availability constraint for period 1, taking into consideration the extra machines introduced through the machine procurement option. In period 1, the total number of machine of each type available is equal to the machine availability (before procurement) plus the number of machines procured in the same period 1. Therefore, if  $A_{m(t=1)} = 0$ , there are no machines present in the system initially, meaning that a CM system is being designed and implemented from no existing manufacturing layout. If  $A_{m(t=1)} > 0$ , there are machines already available in the system, meaning that the existing manufacturing layout is being reconfigured to form a CM layout. Constraint (15) relates to the machine availability constraint for the subsequent time periods. It takes into

consideration the extra machines introduced through the machine procurement option in the period under consideration as well as those procured in all of the previous periods. Constraint (16) ensures that the total number of machines in each cell will not exceed the number of available machines. Constraint (17) is the logical binary and non-negativity integer requirements on the decision variable.

#### 4. Linearization of the objective function

Objective function is a nonlinear integer equation due to nonlinear terms (1.9) and (1.12) in the objective function and also constraints (3), (9) and (10). To transform these terms to linear terms, the following new variables are defined (Mahdavi et al. [19]):

$$F_{pct} = v_{pct} * \beta_{pt} J_{pmwct} = z_{pmwct} * \beta_{pt}$$

By considering these equations, following constraints must be added to the model:

$$F_{pct} \geq \beta_{pt} - L^p (1 - v_{pct}) \quad \forall (p, c, t) \quad (18)$$

$$F_{pct} \leq \beta_{pt} + L^p (1 - v_{pct}) \quad \forall (p, c, t) \quad (19)$$

$$J_{pmwct} \geq \beta_{pt} - L^p (1 - z_{pmwct}) \quad \forall (p, m, w, c, t) \quad (20)$$

$$J_{pmwct} \leq \beta_{pt} + L^p (1 - z_{pmwct}) \quad \forall (p, m, w, c, t) \quad (21)$$

$$F_{pct} \geq 0 \text{ and is integer } \forall (p, c, t) \quad (22)$$

$$J_{pmwct} \geq 0 \text{ and is integer } \forall (p, m, w, c, t) \quad (23)$$

Also to linearize the proposed model, constraint (3) should be replaced by these two constraints:

$$\sum_{m=1}^M \sum_{w=1}^W z_{pmwct} \leq L^p * \beta_{pt}, \quad \forall (p, c, t) \quad (24)$$

$$\sum_{m=1}^M \sum_{w=1}^W z_{pmwct} \geq \beta_{pt}, \quad \forall (p, c, t) \quad (25)$$

Therefore, the proposed linear mathematical programming model is as follows:

Min

$$\text{Eq. (1.1) to Eq. (1.8) } + \sum_{t=1}^T \sum_{p=1}^P [(\sum_{c=1}^C F_{pct}) - \beta_{pt}] \cdot V_p^{inter} + \text{Eq. (1.10) } + \text{Eq. (1.11) } + \sum_{t=1}^T \sum_{p=1}^P \sum_{m=1}^M \sum_{w=1}^W \sum_{c=1}^C J_{pmwct} * t_{pmw} * Y_m$$

St.:

Constraints (2), (4) - (8), (11) - (25) and the new version of constraints (9) and (10) are:

$$\sum_{m=1}^M \sum_{p=1}^P J_{pmwct} * t_{pmw} \leq N_{wct} * RW_{wt}, \quad \forall (w, c, t) \quad (26)$$

$$\sum_{w=1}^W \sum_{p=1}^P J_{pmwct} * t_{pmw} \leq N_{mct} * T_{mt}, \quad \forall (m, c, t) \quad (27)$$

Table 1 shows the numbers of variables and the number of constraints in the linearized model, respectively.

**Table 1** Number of variables and constraints

Number of Variables					
Variables	Count	Variables	Count	Variables	Count
$N_{mct}$	$M \times C \times T$	$Q_{pt}$	$P \times T$	$N_{wct}$	$W \times C \times T$
$Y_{mct}^+$	$M \times C \times T$	$\beta_{pt}$	$P \times T$	$v_{pct}$	$P \times C \times T$
$Y_{mct}^-$	$M \times C \times T$	$O_{pt}$	$P \times T$	$z_{pmwct}$	$P \times M \times W \times C \times T$
$BN_{mt}$	$M \times T$	$L_{wct}^+$	$W \times C \times T$	$F_{pct}$	$P \times C \times T$
$A_{mt}^*$	$M \times T$	$L_{wct}^-$	$W \times C \times T$	$J_{pmwct}$	$P \times M \times W \times C \times T$
<b>Total = <math>3(M \times C \times T) + 2(M \times T) + 3(P \times T) + 3(W \times C \times T) + 2(P \times C \times T) + 2(P \times M \times W \times C \times T)</math></b>					
Number of Constraints					
Constraint	Count	Constraint	Count	Constraint	Count
2	$P \times T$	13	$P \times T$	21	$P \times M \times W \times C \times T$
4	$P \times M \times W \times T$	14	M	24	$P \times C \times T$
5	$P \times M \times T$	15	$M \times T$	25	$P \times C \times T$
6	$M \times C \times T$	16	$M \times T$	26	$W \times C \times T$
7	$2 \times (C \times T)$	18	$P \times C \times T$	27	$M \times C \times T$
11	$W \times C \times T$	19	$P \times C \times T$	28	P
12	$W \times T$	20	$P \times M \times W \times C \times T$	29	W
22	$P \times C \times T$	23	$P \times M \times W \times C \times T$		
<b>Constrain 17 : <math>3 \times (M \times C \times T) + 3 \times (W \times C \times T) + 3 \times (P \times T) + 2 \times (M \times T) + (P \times C \times T) + (P \times M \times W \times C \times T)</math></b>					
<b>Total = <math>5(P \times C \times T) + 3(P \times M \times W \times C \times T) + 2(M \times T) + 2(M \times C \times T) + 2(W \times C \times T) + M + P + W + 2(C \times T) + 2(P \times T) + (P \times M \times W \times T) + (P \times M \times T) + 3(M \times C \times T) + 3(W \times C \times T) + 3(P \times T) + 2(M \times T) + (P \times C \times T) + (P \times M \times W \times C \times T)</math></b>					

## 5. Numerical Examples

In this section, we present full details and discussion for two examples in order to demonstrate the proposed CMS model. In these two examples we used the same input data that Mahdavi et al. [19] used. Since their model is different than our proposed model, we added some additional cost parameters for the features that are not addressed in their model, such as the costs of machine procurement, outsourcing, and operating the machines. The unknown cost parameters, which proved to be more difficult to obtain, were extracted by cross-referencing between the data sets containing them and, afterwards, by incorporating within the other data sets that are missing that information. Therefore, all of the data sets used in each numerical example solved contain values within the same range in terms of unit costs.

The model were solved using IBM ILOG CPLEX Optimization Studio 12.2/OPL and run with Intel core 5 and 6 GB RAM workstation.

### 5.1 Example 1

This example includes two cells, three machines, four parts, two periods, and four workers. The number of variables for such system is 605 and the number of constraints is 683. The related information is given in Tables 2, 3, 4, and 5.

Table 2 shows the machine information; quantity available of machine, relocation cost, procurement cost, time capacity, operating cost per unit time and

overhead and maintenance cost. In this example, we assume that the number of available machines for all types is equal to zero. In other words, we need to establish a new manufacturing facility to show the benefits of the new factor (i.e. Machine Procurement Cost). Table 3 shows the processing time per part per hour for each part type on each machine type produced by each worker. For example, part type 3 must be processed on machine type 1 with processing time 0.02h by worker 1 or with processing time 0.03h by worker 2. The data set related to the machine-part and machine-worker incidence matrices are shown in Tables 4 and 5, respectively. For instance, as seen in Table 4, machine types 2 and 3 are required for part type 4. Table 4 also shows the input data: demand per each period for each part type, holding cost for each part per each period, outsourcing cost for each part per each period and inter-cell material handling cost. Table 5 shows the input data for the workers; available workers for each type, salary cost for each type for each period, hiring cost for each type for each period, firing cost for each type for each period and available time for each type for each period. Table 5 also shows workers' capabilities in working with different machines. For example, worker 3 is able to work with machines type 2 and 3. Moreover, the number of cells to be formed is two and the minimum and maximum cell sizes for each cell sizes are 1 and 4, respectively. The minimum size of each cell in terms of the number of workers is assumed to be one.

**Table 2 Machine information.**

Machine Information for Example 1								
Machine Type	Machine Information							
	$A_m$	$OV_m$	$R_m^+$	$R_m^-$	$T_{m1}$	$T_{m2}$	$Y_m$	$OP_m$
1	0	400	550	140	30	30	15	3000
2	0	410	530	130	30	30	13	4000
3	0	430	560	150	30	40	14	5000
Machine Information for Example 2								
	$A_m$	$OV_m$	$R_m^+$	$R_m^-$	$T_{mt}$		$Y_m$	$OP_m$
1	0	520	600	100	40 40 40		18	3000
2	0	510	650	150	40 40 40		16	4000
3	0	550	660	200	40 40 40		14	5000

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**Table 3 The Processing Time for both Example 1 and 2.**

	Part1				Part2				Part3				Part4			
	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4
M1	0.04	0.02			0.04	0.01			0.02	0.03						
M2			0.02	0.03			0.04	0.03							0.03	0.02
M3	0.01		0.02						0.01		0.02		0.03		0.04	

**Table 4 The input data of machine-part incidence matrix.**

The input data of machine-part incidence matrix for Example 1														
Part Type	Machine Type				$D_{p1}$	$D_{p2}$	$\xi_p$	$H_{p1}$	$H_{p2}$	$U_{p1}$	$U_{p2}$	$V_p^{inter}$		
	1	2	3	4										
1	1	1	1	1	0	1550	20	4	4	80	80	11		
2	1	1	0	0	900	600	21	6	6	82	82	9		
3	1	0	1	1	1700	500	23	8	8	90	90	8		
4	0	1	1	1	1700	300	24	10	10	100	100	10		

  

The input data of machine-part incidence matrix for Example 2															
Part Type	Machine Type				$D_{p1}$	$D_{p2}$	$D_{p3}$	$\xi_p$	$H_{p1}$	$H_{p2}$	$H_{p3}$	$U_{p1}$	$U_{p2}$	$U_{p3}$	$V_p^{inter}$
	1	2	3	4											
1	1	1	1	1	0	1550	500	20	1	1	1	80	80	80	5
2	1	1	0	0	600	800	1000	21	2	2	2	82	82	82	6
3	1	0	1	1	1200	1000	500	23	3	3	3	90	90	90	4
4	0	1	1	1	1200	900	900	24	4	4	4	100	100	100	3

**Table 5 The input data of machine-worker incidence matrix**

The input data of machine-worker incidence matrix for Example 1															
Worker Type	Machine Type			Worker Information											
	1	2	3	$A_w$	$S_{w1}$	$S_{w2}$	$S_{w3}$	$HI_{w1}$	$HI_{w2}$	$F_{w2}$	$RW_{w1}$	$RW_{w2}$			
1	1	0	1	2	470	490		270	285	145	30	30			
2	1	0	0	2	460	485		260	290	145	30	30			
3	0	1	1	2	455	475		200	250	155	30	30			
4	0	1	0	2	450	480		265	280	140	30	30			

  

The input data of machine-worker incidence matrix for Example 2															
Worker Type	Machine Type			$A_w$	$S_{w1}$	$S_{w2}$	$S_{w3}$	$HI_{w1}$	$HI_{w2}$	$HI_{w3}$	$F_{w2}$	$F_{w3}$	$RW_{w1}$	$RW_{w2}$	$RW_{w3}$
	1	2	3												
1	1	0	1	2	400	450	450	230	285	285	110	145	40	40	40
2	1	0	0	2	420	465	465	220	290	290	120	145	40	40	40
3	0	1	1	2	415	475	475	200	250	250	115	155	40	40	40
4	0	1	0	2	430	480	480	245	280	280	120	140	40	40	40

The results are shown in Tables 6, 7, and 8. Tables 6 and 7 show the optimal production plan and the objective function value respectively. Table 8 shows the part families, machine groups, and worker assignments. As mentioned above, in this example we need to build a new manufacturing facility that does not have any old machines, so that we need to buy new machines. Thus, we need to buy at the beginning of the first period two machines of type 1 and 2, and three machines of type 3. The total cost of buying these machines can be found in Table 6 (Procurement

cost = \$29,000). In Table 6, we see that the demand of part type 1 in the first period is zero but we need to produce some quantity, which will be held to the next period to satisfy a portion of demand in the coming periods. We can also note that the demand for part type 4 in the first period is 1700 while the production is 1500. The shortage quantity (200 units) will accordingly be satisfied by outsourcing. Part type 4 will be processed in cell 2 during the first period, this will be done by machines type 2 and 3 by workers type 1 and 4. In the second period part type 4 will be



**Table 6 Optimal Production Plan**

Optimal Production Plan for Example 1												
	Period 1				Period 2							
	P1	P2	P3	P4	P1	P2	P3	P4				
Outsourcing					200							
Holding	50											
Production	50	900	1700	1500	1500	600	500	300				
Demand	0	900	1700	1700	1550	600	500	300				

  

Optimal Production Plan for Example 2												
	Period 1				Period 2				Period 3			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
Outsourcing												
Holding	4	12			82							
Production	4	612	1200	1282	1546	788	1000	818	500	1000	500	900
Demand	0	600	1200	1200	1550	800	1000	900	500	1000	500	900

**Table 7 Objective Function value and its components**

Objective Function value and its components for Example 1												
Total	Outsourcing	Holding	Inter-cell movement	Maintenance and overhead	Machine Procurement	Production cost	Operating cost	Machine relocation	Salary	Hiring	Firing	
224662	20000	200	0	5390	29000	156300	2852	840	6100	3695	285	

  

Objective Function value and its components for Example 2												
Total	Outsourcing	Holding	Inter-cell movement	Maintenance and overhead	Machine Procurement	Production cost	Operating cost	Machine relocation	Salary	Hiring	Firing	
291523	0	356	0	5770	24000	225500	28172	200	6255	1125	145	

**Table 8 The result of parts, machines and workers Assignments**

The result of parts, machines and workers Assignments for Example 1						
	Parts assigned to		Machines in		Workers assigned to	
	Cell1	Cell2	Cell1	Cell2	Cell1	Cell2
Period1	1,2,3	4	1,1,2,3	2,3,3	1,1,2,4	3,3,4
Period2	2,3,4	1	1,2,3	1,2,3	1,2,4	2,3,3

  

The result of parts, machines and workers Assignments for Example 2						
	Parts assigned to		Machines in		Workers assigned to	
	Cell1	Cell2	Cell1	Cell2	Cell1	Cell2
Period1	1,2,4	3	1,2,2,3	1,3	1,2,3,4	1
Period2	1,2,4	3	1,2,2,3	1,3	1,2,3,4	1
Period3	1,2,3,4		1,2,2,3	1	1,2,3,4	1

processed in cell 1 by the same machines and the same worker types. Moreover part type 2 will be processed in cell 1 during the first and second period by machines type 1 and 2 by workers type 1, 2, and 4.

Table 8 shows the distribution of the machines between cells in the first period and their relocation in the second period; one machine of both type 2 and 3, and 2 machines of type 1 are assigned to the first cell

during the first period, and the remaining machines are assigned to the second cell (two machines of type 3, and one machine of type 2), the relocation in the second period consist of moving one machine type 1 from the first cell as well as one machine of type 3 from the second cell, also, it consist of installing one machine of type 1 in the second cell. Table 8 additionally shows the distribution for the workers in

the two periods; cell 1 needs in the first period two workers of type 1 and one worker of both types 2 and 4, in the second period one worker of type 1 will be fired, on the other hand, cell 2 needs in the first period one worker of type 4 and two workers of type 3, in the second period one worker of type 2 will be hired and on worker of type 4 will be fired.

System design for this example and the allocation of workers, machines, and parts are shown in Figure 1. The system relocation actions are also shown in the same figure as well as system design after relocation (system design for period 2). In the second period, we have two workers fired and one unused machine; machine of type 3, in which case we can hold the machine to be used in the coming period, or we can sell it.

From the above example, the benefit of introducing the human issues in the proposed model can be seen clearly; the main actions during the relocation of the system above is firing two workers, one worker of type 1 and one worker of type 4, and hiring of one worker of type 2. By this action a salary of one worker will be saved. Therefore, the demands in the second period of all part types will be satisfied by six workers

instead of seven workers in the first period. It is shown also that the demand in the second period will be satisfied by six machines instead of seven machines, since that one machine of type 3 is no longer needed. On the other hand, this machine can be held for the next period, if it is needed, or it can be sold.

*5.2 Example 2*

This example includes two cells, three machines, four parts, three periods, and four workers. The number of variables for such system is 829 and the number of constraints is 1013. Machine Information, processing input data of machine-worker incidence matrix, time input data of machine-part incidence matrix, are given in Tables 2, 3, 4, and 5, respectively. Moreover, the number of cells to be formed is two and the minimum and maximum cell sizes for each cell are 1 and 5, respectively. The minimum size of each cell in terms of the number of workers is assumed to be one.

The optimal results have been shown in Tables 6, 7, and 8. Tables 6 and 7 show the optimal production plan and the objective function value, respectively.



**Fig. 1** System layout and relocation for Example 1.

Table 8 shows the part families, machine groups, and worker assignments.

We need to buy new machines, thus we need to buy at the beginning of the first period two machines of each type. The total cost of buying these machines can be found in Table 7 (Procurement cost = 24000). We can also see from Table 6 that by not outsourcing parts, we can match this cost by zero for outsourcing in Table 7. We can conclude that the demand of all parts in each period will satisfy by internal production and inventory. In Table 7 we can see that the inter-cell cost is equal to zero, which means that each part will be produced completely in its own cell. In other words, all operations that the part needs will be done in one cell (no moving between cells will occur). System

design for this example and the allocation of workers, machines, and parts are shown in Fig. 2. In addition, the system relocation actions are shown. For the system design after relocation (system design for period 2), since the example is a three-period problem, a second relocation should be done (Fig. 2). After the second relocation the system design for the third period has been achieved and this can be seen in Fig. 2. It is clearly seen from Fig. 2 that no changes will be done on the system design between period 1 and period 2, which means that this system design is the optimal configuration for both periods 1 and 2. After the second relocation, an optimal system design has been formed for period 3 (Fig. 2).

Since all the products will be produced in the first



Fig. 2 System layout and relocation for Example 2

cell, cell 2 will not be used for the third period production. There is one machine and one worker assigned to this cell to satisfy the conditions that expressed in the model's constraints; number (7) and (8), which are explained in section 3.2.

Constraint (7)  $\{LB_c \leq \sum_{m=1}^M N_{mct} \leq UB_c; \forall(c, t)\}$ , enforces the number of machines assigned to each cell in each period to be not less than the lower limit (in this example it is 1) and not more than the upper limit (in this example it is 5). Constraint (8)  $\{\sum_{w=1}^W N_{wct} \geq Lwc, \forall(c, t)\}$ , enforces the number of workers assigned to each cell in each period to be not less than the lower limit (in this example it is 1). So these constraints do not take into account whether the cell will be used for production during a specific period or not.

It is clearly shown from the above example that the demand in the third period will be satisfied by using one cell, four workers, and four machines as opposed to two cells, five workers, and six machines in the previous two periods (period one and two). In other words, the system in the third period no longer needs the second cell, one worker of type one, and two machines of both types one and three. Hence, all of these lead to cost savings.

It is seen from the above two examples that considering the workforce management issues (worker assignments) is one of the most important factors that should be taken into account when designing a Cellular Manufacturing Systems (CMSs). Considering such factors gives a comprehensive review of the system, good tracking, and since there exist variations in the demand and variety in the products, the system does not need the same team of workers in each period. Accordingly, a relocation of the workers should be taken into consideration along with the machines and products. Ignoring this factor can considerably reduce the efficiency of the cellular manufacturing.

### 5.3 Sensitivity Analysis

Another aspect of the model to be discussed relates

to the relationship between the flexible manufacturing systems and optimal inventory systems by explaining how workers' hiring-firing costs ( $HI_{wt}, F_{wt}$ ) are related to holding cost ( $H_{pt}$ ) of the pre-processed products. A number of tests were run in order to determine the effect of varying the levels of such costs and the results are shown in table 9 below. The values for the hiring-firing cost of each worker type vary from \$0 (very low) to \$500 (very high). The values for inventory holding cost per part type vary from \$0 (very low) to \$20 (very high). Table 9 shows how the CM system adjusts to various hiring-firing and inventory holding costs combinations and also presents relevant information on each optimal CM configuration.

We can see how introducing the workforce management in designing a CM system increases the flexibility of such systems. It is observed that when the holding cost is too high (\$20) and the hiring-firing cost is too low (\$0), the demand will be satisfied by hiring and firing many workers. On the other hand when the opposite case occurs (i.e. low holding cost (\$0) and high hiring-firing cost (\$500)) the demand will be satisfied by holding a high volume of inventory and by hiring the minimum number of workers required without firing any worker.

## 6. Conclusions and Future Research

In this paper, an integer nonlinear programming model for dynamic cellular manufacturing systems has been developed. The model integrates many manufacturing attributes such as production planning, machine cost, machine capacity as well as several workforce management issues such as worker capacities, worker assignments, salary, hiring and firing costs for the workers. We emphasized that ignoring human related aspects in designing a cellular manufacturing system can significantly reduce the benefits that accrue from this mode of manufacturing. The optimization model developed addresses to such workforce related issues and its results provide answers to when, where, and

**Table 9 Total system costs when varying hiring-firing cost and inventory holding costs values**

Cost combination	Total cost	Remarks	Cost combination	Total cost	Remarks
$HI_{wt}, F_{wt} = 500$ $H_{pt} = 0$	189,939	Hired workers: 1 worker of type 1 in period 1 1 worker of type 2 in period 1 0 worker of type 3 1 workers of type 4 in period 1 No fired workers Inventories will be: 1549 units of part 1 0599 units of part 2 0499 units of part 3 0299 units of part 4	$HI_{wt}, F_{wt} = 250$ $H_{pt} = 10$	189,243	Hired workers: 1 worker of type 1 in period 1 1 worker of type 2 in period 1 1 worker of type 3 in period 1 1 worker of type 4 in period 1 No fired workers Zero Inventory
$HI_{wt}, F_{wt} = 0$ $H_{pt} = 20$	188,069	Hired workers: 1 worker of type 1 in period 1 1 worker of type 2 in period 1 2 workers of type 3 in period 2 2 workers of type 4 period 1 Fired workers: 1 worker of type 1 in period 2 2 workers of type 4 in period 2 Zero inventory	$HI_{wt}, F_{wt} = 0$ $H_{pt} = 10$	188,059	Hired workers: 1 worker of type 1 in period 1 1 worker of type 2 in period 1 2 workers of type 3 in period 2 2 workers of type 4 in period 1 Fired workers: 1 worker of type 1 in period 2 2 workers of type 4 in period 2 Zero Inventory
$HI_{wt}, F_{wt} = 500$ $H_{pt} = 20$	190,177	Hired workers: 1 worker of type 1 in period 1 0 worker of type 2 0 worker of type 3 2 workers of type 4 period 1 No fired workers: Zero inventories	$HI_{wt}, F_{wt} = 250$ $H_{pt} = 0$	188,782	Hired workers: 1 worker of type 1 in period 1 2 workers of type 2 in period 1 0 worker of type 3 1 worker of type 4 period 1 Fired workers: 1 worker of type 2 in period 2 Inventories will be: 1549 units of part 1 0599 units of part 2 0499 units of part 3 0299 units of part 4
$HI_{wt}, F_{wt} = 0$ $H_{pt} = 0$	187,027	Hired workers: 1 worker of type 1 in period 1 1 worker of type 2 in period 1 1 worker of type 2 in period 2 1 worker of type 3 in period 1 2 workers of type 4 period 1 Fired workers: 1 worker of type 1 in period 2 1 worker of type 2 in period 2	2 workers of type 4 in period 2 Inventories will be: 1549 units of part 1 0599 units of part 2 0499 units of part 3 0299 units of part 4		

whom to hire or fire. The model also identifies the part families and machine groups concurrently. It, additionally, specifies the plans selected for each part, quantity to be produced or to be procured during each time period, machine type to perform each operation, and the total number of machines required. Linearization techniques have been used to transform the model into an integer linear programming formulation. Some numerical examples were solved using the linearized model. In these examples, the

largest small problem was successfully solved in less than 10 seconds. Medium-size problems could be solved within up to 1 hour. Larger sized problems prove to be more difficult to solve using the proposed approach. We provided two numerical examples in detail; including the data used, the solutions, and the analysis of the results obtained. The solutions from the proposed model have shown that CM structural and operational design decisions that were not addressed in the models previously developed and reported in

the literature can be addressed with the DCMS model proposed in this article. The future work in this research will be on the investigation of the use of meta-heuristics, especially Tabu Search, Simulated Annealing and Genetic Algorithms, to solve problems of larger scales for this integrated CMS model.

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