

ORIGINAL RESEARCH

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A multi-objective model for designing a group layout of a dynamic cellular manufacturing system

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Abstract

This paper presents a multi-objective mixed-integer nonlinear programming model to design a group layout of a cellular manufacturing system in a dynamic environment, in which the number of cells to be formed is variable. Cell formation (CF) and group layout (GL) are concurrently made in a dynamic environment by the integrated model, which incorporates with an extensive coverage of important manufacturing features used in the design of CMSs. Additionally, there are some features that make the presented model different from the previous studies. These features include the following: (1) the variable number of cells, (2) the integrated CF and GL decisions in a dynamic environment by a multi-objective mathematical model, and (3) two conflicting objectives that minimize the total costs (i.e., costs of intra and inter-cell material handling, machine relocation, purchasing new machines, machine overhead, machine processing, and forming cells) and minimize the imbalance of workload among cells. Furthermore, the presented model considers some limitations, such as machine capability, machine capacity, part demands satisfaction, cell size, material flow conservation, and location assignment. Four numerical examples are solved by the GAMS software to illustrate the promising results obtained by the incorporated features.

Keywords: Dynamic cellular manufacturing systems, Multi-objective model, Cell formation, Group layout

Introduction

Cellular manufacturing (CM), which is an innovative manufacturing strategy derived from a group technology concept, can be employed in order to improve both the flexibility and efficiency in today's modern competitive manufacturing environments (e.g., flexible manufacturing systems and just-in-time production). The design steps of a cellular manufacturing system (CMS) include the following: (1) cell formation (CF) (i.e., clustering parts with similar processing requirements into part families and related machines into machine cells), (2) group layout (GL) (i.e., intra-cell layout arranging machines within each cell, and inter-cell layout arranging cells with regard to each other), and (3) group scheduling (GS) (i.e., scheduling part families) (Wemmerlov and Hyer 1986).

Unplanned changes in the product mix and demand volume necessitate reconfiguration of layouts of modern

manufacturing systems producing multiple products and working in highly unstable environments. Hence, ignoring these changes such as new products in the coming future imposes subsequent unplanned changes to the CMS and causes production disruptions and unexpected costs. As a result, product life cycle changes should be incorporated in the design of cells. This type of the system is called the dynamic cellular manufacturing system (DCMS) (Rheault et al. 1995). Drolet et al. (2008) developed a stochastic simulation model and indicated that DCMSs are generally more efficient than classical CMSs or job shop systems, especially with respect to performance measures (e.g., the throughput time, work-in-process, tardiness, and the total marginal cost) for a given horizon.

Reconfiguring cells incurs the corresponding costs (e.g., moving machines, installing or uninstalling machines, lost production time, and relearning). By considering the reconfiguration costs, it is possible that a suboptimal configuration is the best one to utilize in a period because utilizing this may impose lower reconfiguration and overall costs (Balakrishnan and Cheng 2007). Thus, when creating

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manufacturing cells, it is important to consider the reconfiguration cost of cells.

Since our model integrates CF and GL decisions in a dynamic environment, we actually incorporate a dynamic layout problem in a DCMS model. In this case, an appropriate decision should be made among the available strategies (e.g., purchasing a new machine to meet increased demand requirements, relocating the machine that is underutilized in a cell to another cell where demand requirements are higher, and re-planning the part production) in order to make a trade-off between resultant costs of purchasing machine, reconfiguration, and intra- and inter-cell material handling.

Wemmerlov and Johnson (2000) indicated that the practical implementation of a CMS involves the optimization of many conflicting objectives. For example, minimizing the total cell load variations worsens the objectives of minimizing the outsourcing cost and inter-cell material handling cost because it necessitates some of parts to be outsourced or some of the processing operations in cells to be shifted to another. A detailed description of the multi-objective optimization can be found in Collette and Siarry (2003).

The aim of this paper is to present a multi-objective mathematical model with an extensive coverage of important manufacturing features consisting of alternative process routings, operation sequence, processing time, production volume of parts, purchasing machine, duplicate machines, machine capacity, lot splitting, group layout, multi-rows layout of equal area facilities, flexible reconfiguration of cells, variable number of cells, and balancing of the cell workload. The first objective of our presented model related to cost components is to minimize the total costs of intra- and inter-cell material handling, machine relocation, purchasing new machines, machine overhead cost, machine processing, and forming of cells. The second objective is to minimize the imbalance of workload among cells.

The model presented in this study is an extended version of the integrated model proposed by Kia et al. (2012) in which the excellent advantages are (1) multi-rows layout of equal-sized facilities, (2) flexible configuration of cells, (3) calculating relocation cost based on the locations assigned to machines, (4) distance-based calculation of intra- and inter-cell material handling costs, (5) considering intra-cell movements between two machines of a same type, (6) applying the equations of material flow conservation, and (7) integrating the CF and GL decisions in a dynamic environment.

This study also incorporates some other important aspects in comparison with the previous study carried out by Kia et al. (2012) and the models presented in the literature. In the first aspect, finding the optimal number of cells provides the flexibility for the model to form cells in optimal numbers to reduce the total costs especially because of simultaneously reducing the cost of forming cells

and improving the CM utilization. In the second aspect, we consider two conflicting objectives that minimize the total costs and minimize the imbalance of workload among cells. In the third aspect, the CF and GL decisions are integrated in a dynamic environment by a multi-objective mathematical model incorporating with several design features. The importance of the incorporated features in improving the performance of the extended model is revealed by numerical examples.

The remainder of this paper is organized as follows. The literature review related to the DCMS, GL, and multi-objective cell formation problem is presented in the 'Literature review' section. In the 'Mathematical model' section, a multi-objective mathematical model integrating DCMS and GL decisions is presented. 'Computational results' section illustrates the test problems that are utilized to investigate the features of the presented model. Finally, conclusion is given.

Literature review

In this section, we present the related literature review of studies addressing layout problems, multi-objective mathematical modeling, and dynamic issues in designing a CMS. Since a comprehensive literature review related to layout problems and dynamic issues in designing a CMS has been done by Kia et al. (2012), here we summarize recent studies of DCMS issue in Table 1.

A list of important features proposed for the CM design is given in Table 2. We investigate 23 recently published papers considering the majority of corresponding features as presented in Table 2. The model presented in this paper includes a larger coverage of the features than the individual papers presented in Table 1.

Mathematical model

In this section, the integrated problem is formulated under the following assumptions:

1. Each part type has a number of operations that must be processed based on its operation sequence.
2. The demand for each part type in each period is known.
3. The capabilities of part operations processing and processing time of part operations for each machine type are known.
4. Each machine type has a limited capacity expressed in hours during each time period.
5. Machines can have one or more identical duplicates to satisfy capacity requirements.
6. The overhead cost of each machine type is known and implies maintenance and other overhead costs, such as energy cost and general service.
7. It is assumed that in the first period, there is no machine available to utilize. Hence, it is needed to purchase some machines to meet part demands. In the next periods, if the existing time capacity of the

Table 1 Important features in the CM design used in this research and other recent studies

Studies	1	2	3	4	5	6	7	8	9	10	11	12		13	14	15	16	17	18	19	20	21		22		23	24		Solution method	
												a	b									a	a	b	a		b			
Present study	x		x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x		x			x	x	x		x		NSGA II
Kia et al. (2012)	x			x		x		x	x	x	x	x		x	x	x	x	x	x						x	x		x		SA
Javadian et al. (2011)	x			x	x	x			x	x	x	x	x	x	x	x	x	x			x	x		x	x	x		x		NSGA II
Jolai et al. (2012)			x	x				x									x								x	x				EM
Rafiee et al. (2011)	x			x		x	x		x	x		x		x	x	x	x	x	x			x	x		x	x	x	x		PSO
Rezazadeh et al. (2011)	x			x	x			x		x				x		x	x	x				x			x					PSO
Ghotboddini et al. (2011)	x	x	x	x		x			x	x	x	x		x	x	x	x	x						x	x			x		BD
Mahdavi et al. (2011)	x	x		x										x	x	x		x			x	x			x			x		FGP
Deljoo et al.(2010)	x			x		x			x	x		x		x	x	x	x	x							x			x		GA
Saxena and Jain (2011)	x			x	x	x	x		x	x	x	x		x	x	x	x	x	x			x	x		x	x		x		Lingo solver
Ahkioon et al. (2009a)	x			x		x			x	x	x	x		x	x	x	x	x							x	x		x		CPLEX solver
Ahkioon et al. (2009b)	x			x		x										x	x											x		CPLEX solver
Safaei et al. (2008)	x			x		x					x	x		x	x	x	x	x					x		x	x		x		HSA
Defersha and Chen (2006)	x		x	x	x	x			x	x	x			x	x	x	x	x	x				x	x				x		Lingo solver
Defersha and Chen (2008)	x			x	x	x			x	x	x			x	x	x	x	x	x				x	x				x		GA
Mahdavi et al. (2010)	x	x		x		x				x	x	x		x	x	x	x	x				x	x					x		Lingo solver
Safaei and Tavakkoli-Moghaddam (2009)	x			x		x				x	x	x		x	x	x	x	x						x	x		x			Lingo solver
Safaei et al. (2010)				x			x				x			x	x		x						x		x	x		x		IFP
Aramoon Bajestani et al. (2009)	x			x	x	x			x	x	x	x		x	x	x	x	x										x		SS
Wu et al. (2007)				x				x									x	x							x	x				GA
Nsakanda et al. (2006)				x										x			x	x						x	x		x			GA
Cao and Chen (2005)	x			x						x				x		x	x	x					x	x	x					TS
Solimanpur et al. (2004)				x	x			x	x	x				x			x	x									x			GA
Mungwattana (2000)	x			x		x			x	x	x	x		x	x	x	x	x									x			SA

BD, Bender's decomposition; EM, electromagnetism-like method; FGP, fuzzy goal programming; GA, genetic algorithm; HSA hybrid simulated annealing; IFP interactive fuzzy programming; NSGA-II elitist non-dominated sorting genetic algorithm; PSO, particle swarm intelligence; SA, simulated annealing; SS, scatter search; TS, Tabu search.

Table 2 List of important features in CM design

Number	Feature
1	Multi-period planning
2	Human resource assignment
3	Variable number of cells
4	Limitation of cell size
5	Workload balancing among cells
6	Cell reconfiguration
7	Reliability
8	Machine layout
9	Purchasing machine cost
10	Machine operation cost
11	Machine overhead cost
12	Machine relocation cost
a	among cells
b	between cells and machine depot
13	Machine capacity
14	Duplicate machines
15	Dynamic demand
16	Operation sequence
17	Operation time
18	Lot splitting
19	Backorder
20	Inventory holding
21	Setup cost/time
22	Material handling cost
a	Inter-cell material handling cost
b	Intra-cell material handling cost
23	Outsourcing
24	Alternative routing
a	Selecting the best route from the user-specified routings
b	Cooperating all possible process routes

machines cannot satisfy the part demand, some other machines will be purchased and added to the currently utilized machines.

8. The variable cost of each machine type implying the operating cost of that machine is dependent on the workload assigned to the machine and is known.
9. Cell reconfiguration involves transferring of the existing machines between different locations and purchasing and adding new machines to cells.
10. To reconfigure the cells, there is no need to alter the foundations or modify the buildings. By considering this assumption, reassigning machines to cells will not impose any reconfiguration cost, unless the machines are relocated between different locations.
11. The transferring cost of each machine type between two periods is known. This cost is paid for two situations: (1) to install a newly purchased machine and (2) to transfer a machine between two locations of

a same cell or different cells. In addition, it is assumed that the unit cost of adding or removing a machine to/from the cells is half of the machine transferring cost.

12. Inter- and intra-cell movements related to the part types have different costs. The material handling cost of inter- and intra-cell movements is related to the distance traveled. In other words, it is assumed that the distance between each pair of machines is dependent on locations assigned to those machines. Machines should be placed in the locations, whose distance from each other is known in advance, and therefore the distance matrix, $D = [d_{ll'}]$, is known where $d_{ll'}$ represents the distance between locations l and l' ($l, l' = 1, \dots, L$). All machine types have the same dimensions and are placed in the locations also with the same dimensions.
13. The maximum number of cells which can be formed in each period must be specified in advance. However, the number of cells which should be formed in each period is considered as a decision variable.
14. The maximum and minimum of the cell size are known in advance.
15. All machine types are assumed to be multi-purposed ones, which are capable to perform one or more operations without imposing a reinstalling cost. In the same manner, each operation of a part type can be performed on different machine types with different processing times.
16. A part operation can be distributed between several machines which are capable to process that operation within the same cell or even in different cells (lot splitting).
17. The number of locations is known in advance.
18. The workload of the cells should be balanced.

The following notations are used in the model:

Sets

- $P = \{1, 2, \dots, P\}$ index set of part types
 $K(p) = \{1, 2, \dots, K_p\}$ index set of operations indices for part type p
 $M = \{1, 2, \dots, M\}$ index set of machine types
 $C = \{1, 2, \dots, C\}$ index set of cells
 $L = \{1, 2, \dots, L\}$ index set of locations
 $T = \{1, 2, \dots, T\}$ index set of time periods

Model parameters

- IE_p inter-cell material handling cost per part type p per unit of distance
 IA_p intra-cell material handling cost per part type p per unit of distance
 D_{pt} demand for part type p in period t

- T_m capacity of one unit of machine type m
- C maximum number of cells that can be formed in each period
- FC_t cost of forming a cell in period t
- B_U upper cell size limit
- B_L lower cell size limit
- t_{kpm} processing time of operation k on machine m per part type p
- $d_{ll'}$ distance between two locations l and l'
- α_m overhead cost of machine type m
- β_m variable cost of machine type m for each unit time
- a_{kpm} 1 if operation k of part p can be processed on machine type m ; 0, otherwise
- γ_m purchase cost of machine type m
- δ_m transferring cost per machine type m
- Decision variables
- $X_{kpm'lt}$ number of parts of type p processed by operation k on machine type m' located in location l' in period t
- W_{mlct} 1 if one unit of machine type m is located in location l and assigned to cell c in period t ; 0, otherwise
- $Y_{kpm'l't}$ number of parts of type p processed by operation k on machine type m located in location l and moved to the machine type m' located in location l' in period t
- Y_{ct} 1 if cell c is formed in period t ; 0, otherwise
- N_{mt}^P number of machine type m purchased in period t

The DCMS mathematical model

The DCMS model is extended and formulated as multi-objective mixed-integer non-linear programming:

$$\min Z_1 = \sum_t \sum_c \sum_m \sum_l \sum_{m'} \sum_{l'} \sum_p \sum_{k_p}^{Kp-1} W_{mlct} \times W_{m'l'ct} \times Y_{kpm'l't} \times d_{ll'} \times IA_p \quad (1.1)$$

$$+ \sum_t \sum_c \sum_{c \neq c'} \sum_m \sum_l \sum_{m'} \sum_{l'} \sum_p \sum_{k_p}^{Kp-1} W_{mlct} \times W_{m'l'c't} \times Y_{kpm'l't} \times d_{ll'} \times IE_p \quad (1.2)$$

$$+ \frac{1}{2} \sum_c \sum_l \sum_m \delta_m \times W_{mlc,t=1} + \frac{1}{2} \sum_t \sum_{l'} \sum_m \delta_m \times \left| \sum_c W_{mlct} - \sum_c W_{mlc,t+1} \right| \quad (1.3)$$

$$+ \sum_t \sum_m \gamma_m \cdot N_{mt}^P \quad (1.4)$$

$$+ \sum_t \sum_m \alpha_m \times \left(\sum_c \sum_l W_{mlct} \right) \quad (1.5)$$

$$+ \sum_t \sum_p \sum_{k_p} \sum_m \sum_l \beta_m \cdot t_{kpm} \cdot X_{kpm'lt} \quad (1.6)$$

$$\sum_t \sum_c FC_t \cdot Y_{ct} \quad (1.7)$$

$$Z_2 = \sum_t \sum_c \left[\sum_m \sum_l \sum_p \sum_k^{Kp} W_{mlct} \cdot X_{kpm'lt} \cdot t_{kpm} - \left(\sum_m \sum_l \sum_p \sum_k^{Kp} X_{kpm'lt} \cdot t_{kpm} \right) / \sum_c Y_{ct} \right] \quad (1.8)$$

s.t.

$$X_{kpm'lt} \leq M \cdot a_{kpm} \quad \forall k \in Kp, \forall p \in P, \forall m \in M, \forall l \in L, \forall t \in T \quad (2)$$

$$D_{pt} = \sum_m \sum_l X_{k=1,pmlt} \quad \forall p \in P, \forall t \in T \quad (3)$$

$$\sum_c \sum_l W_{mlct} = \sum_c \sum_l W_{mlc,t-1} + N_{mt}^P \quad \forall m \in M, \forall t \in T \quad (4)$$

$$\sum_m \sum_l W_{mlct} \leq B_U \cdot Y_{ct} \quad \forall c \in C, \forall t \in T \quad (5)$$

$$B_L \cdot Y_{ct} \leq \sum_m \sum_l W_{mlct} \quad \forall c \in C, \forall t \in T \quad (6)$$

$$\sum_p \sum_k^{Kp} X_{kpm'lt} \times t_{kpm} \leq T_m \sum_c W_{mlct} \quad \forall m \in M, \forall l \in L, \forall t \in T \quad (7)$$

$$X_{kpm'lt} = \sum_{m'} \sum_{l'} Y_{kpm'l't} \quad \forall k \in Kp, \forall p \in P, \forall m \in M, \forall l \in L, \forall t \in T \quad (8)$$

$$X_{kpm'l't} = \sum_m \sum_l Y_{k-1,pmlm'l't} \quad \forall k \in Kp, \forall p \in P, \forall m' \in M, \forall l' \in L, \forall t \in T \quad (9)$$

$$\sum_m \sum_c W_{mlct} \leq 1 \quad \forall l \in L, \forall t \in T \quad (10)$$

$$X_{kpm'lt} \geq 0, Y_{kpm'l't} \geq 0 \text{ and integer} \quad \forall k \in Kp, \forall p \in P, \forall m, m' \in M, \forall l, l' \in L, \forall t \in T \quad (11)$$

$$W_{mlct}, Y_{ct} \in \{0, 1\} \quad \forall m \in M, \forall c \in C, \forall l \in L, \forall t \in T \quad (12)$$

$$N_{mt}^P, N_{mt}^+, N_{mt}^-, O_{pt}, V_{pt} \geq 0 \text{ and integer} \quad \forall p \in P, \forall m \in M, \forall t \in T \quad (13)$$

The first objective function consists of seven cost components. Term (1.1) is the intra-cell material handling

cost. This cost is incurred if consecutive operations of the same part type are processed in the same cell, but on different machines. For instance, operation k of part type p is processed on machine type m assigned to location l in cell c at time t . If the next operation, $k + 1$, of part p is processed on any other machine, but within the same cell, then an intra-cell cost is incurred. The product $W_{mlct} \times W_{m'l'ct}$ in term (1.1) is to verify whether two machines of types m and m' assigned to locations l and l' are in the same cell. If the product reflects 1 as the result, then those machines, which are in a same cell and the material flow between them, impose the intra-cell material handling cost. To calculate this cost, the material flow between the machines assigned in the same cell $\left(Y_{kpmim'l't}\right)$ is multiplied to the distance between the locations of those machines $\left(d_{ll'}\right)$, and then to the intra-cell material handling cost per each part type $\left(IA_p\right)$. This term of the objective function tries to locate two machines having a large quantity of the material flow near each other in order to shorten the distance between them and to assign those machines in the same cell to pay the intra-cell material handling cost $\left(IA_p\right)$ lesser than the inter-cell material handling cost $\left(IE_p\right)$, and finally to take a small portion in the objective function.

In a similar way, term (1.2) denotes the inter-cell material handling cost. This cost is incurred whenever consecutive operations of the same part type are transferred between different cells. For instance, assume that operation k of part type p is processed on machine type m in cell c at time t . If the next operation (i.e., $k + 1$) of part p is processed on any machine, but in another cell, then an inter-cell cost is incurred. To decrease this section of the objective function, it is better to locate two machines having a small quantity of the material flow between each other in different cells rather than those machines having a large quantity of the material flow in order to pay the inter-cell material handling cost $\left(IE_p\right)$ for a smaller quantity of the material flow of parts between different cells.

Term (1.3) represents the reconfiguration cost of cells occurring in (1) installing a new purchased machine or (2) transferring a machine between two locations in the cells. The component $\left|\sum_c^C W_{mlct} - \sum_c^C W_{mlc,t+1}\right|$ in term (1.3) quests whether machine type m assigned to location l in period t remains in the same location for subsequent period, $t + 1$. The component $\left|\sum_c^C W_{mlct} - \sum_c^C W_{mlc,t+1}\right|$ equaling to value 1 means that an installation or uninstallation of machine type m in location l is happened. Thus, based on Assumption (11), a half of transferring machine cost $\left(\delta_m\right)$ for machine type m should be paid. In the other hand, the component $\left|\sum_c^C W_{mlct} - \sum_c^C W_{mlc,t+1}\right|$ equaling to value 2 means a transferring of machine type m between two different locations in the cells has happened and a complete transferring machine cost $\left(\delta_m\right)$ for machine type m should be paid. The

first part in Term (1.3) (i.e., $1/2 \sum_c^C \sum_l^L \sum_m^M \delta_m \times W_{mlc,t=1}$) calculates installation costs for the newly purchased machines in the first period ($t = 1$).

Term (1.4) is the purchase costs of new machines. Term (1.5) incorporates the overhead costs. Term (1.6) takes into account the operating costs of all machine types. Term (1.7) is the total costs of forming cells.

The second objective function pertains to the total cell load variation. Balancing workload between the cells reduces work-in-process inventory, improves material flow through the cells, and prevents overutilization of some cells and underutilization of others (Baykasoglu et al. 2001). In this paper, the total cell load variation in each period is measured by calculating the absolute deviation between the workload of each cell and average workload of cells.

Inequality (2) guarantees that each operation of a part is processed on the machine, which is capable to process that operation. Constraint (3) shows that the demand of each part should be satisfied in a period through internal production. Equation (4) describes that the number of machine type m utilized in the period t is equal to number of utilized machines of the same type in the previous period plus the number of new machines of the same type purchased at the beginning of the current period. The cell size is limited through Constraints (5) and (6), where the cell size lies within the user defined lower and upper bounds. Constraint (7) is related to the machine capacity. Constraints (8) and (9) are material flow conservation equations. Constraint set (10) is to ensure that each location can receive one machine at most and only belong to one cell, simultaneously. Constraints (11) to (13) provide the logical binary and non-negativity integer necessities for the decision variables.

Computational results

Illustrative numerical examples for the single-objective model

To validate the proposed model and illustrate its various features, a test problem taken from the example (Kia et al. 2012) is solved using GAMS 22.0 software (solver CPLEX) (Washington, DC, USA) on an Intel(R) Core (TM)2 Duo CPU @2.66 GHz (Intel Corporation, Santa Clara, CA, USA) with 4 GB RAM. In this section, only the objective function Z_1 cost components is considered to investigate single-objective model features. The information related to the first example is given in Tables 3 and 4. This example consists of four part types, five machine types, and two periods, in which each part type is assumed to have three sequential processing operations. Each operation can be processed on two alternative machines. Five columns of Table 3 contain the information related to the machine time capacity, relocation cost, purchasing machine cost, overhead cost, and machine

Table 3 Machine and part information for the first example

Machine information						P1			P2			P3			P4		
	T_m	δ_m	γ_m	α_m	β_m	1	2	3	1	2	3	1	2	3	1	2	3
M1	500	900	18,000	1,800	9				0.76	0.65	0.39			0.46	0.49	0.83	
M2	500	750	15,000	1,500	7		0.79					0.99		0.33			0.74
M3	500	900	18,000	1,800	5	0.73	0.93	0.44					0.57		0.45		
M4	500	850	17,000	1,700	9			0.46	0.80			0.14					
M5	500	650	13,000	1,300	8	0.54				0.65	0.93		0.48			0.67	0.62
D_{pt}						200			700			300			0		
						500			250			700			300		

operating cost. For more simplicity, the capacity of all machines is assumed to be equal to 500 h per period. Furthermore, the processing time of each operation for all part types are presented in Table 3. In addition, the demand quantity for each part type and the product mix for each period are presented in this table. The forming cell cost, intra- and inter-cell material handling costs per each part type are 20,000; 5; and 50; respectively.

The maximum number of cells formed in each period is four. Also, the lower and upper sizes of cells are 2 and 3, respectively. The distances between eight locations existing in the shop floor are presented in the matrix, as shown in Table 4.

The obtained solution with the model presented in this paper on the explained example is detailed out. Also, to show the advantage of the proposed model and considering the variable number of cells in comparison with to the previous model (Kia et al. 2012), the solutions obtained using two models and their performance are discussed in the rest of this section. The presented model consists of 652,619 variables and 751,238 constraints in the given example. The optimal solution is obtained after 74,159 s (i.e., about 20 h). This reveals the NP-hardness of the presented model even in solving such a small-sized example.

The cell configurations and machine layout for two periods corresponding to the best solutions obtained using the model (Kia et al. 2012) with three cells and the presented model with two optimal cells are shown in

Table 4 Distance matrix between locations

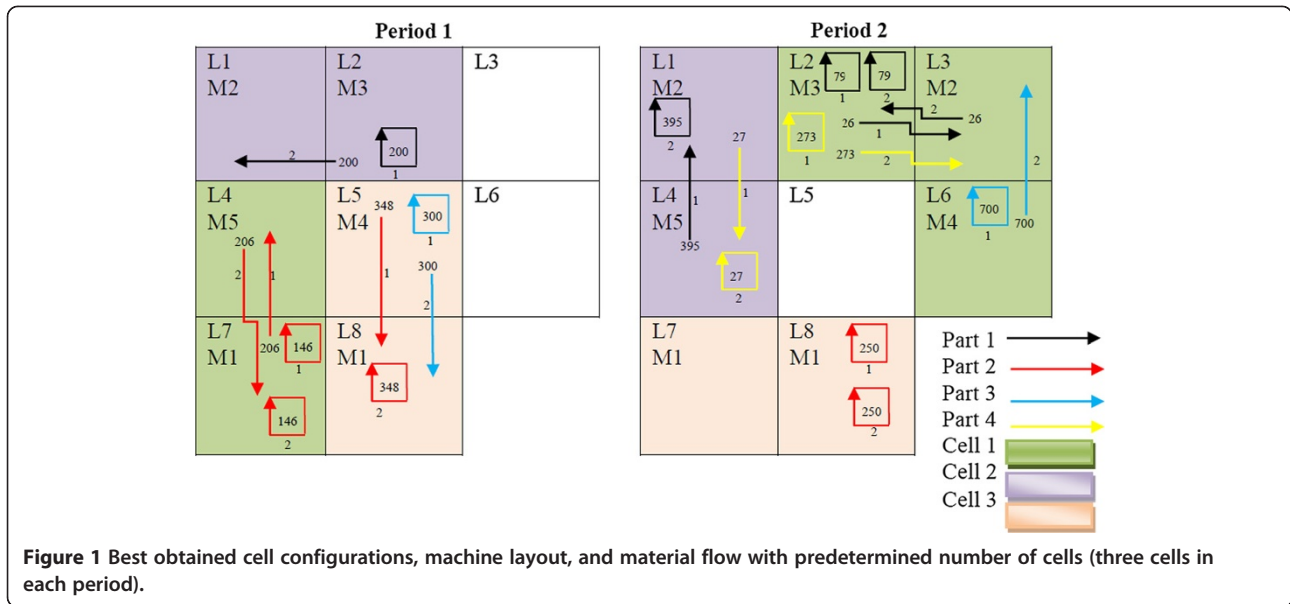
Location	Location							
	L1	L2	L3	L4	L5	L6	L7	L8
0	1	2	1	2	3	2	3	
1	0	1	2	1	2	3	2	
2	1	0	3	2	1	4	3	
3	2	3	0	1	2	1	2	
4	1	2	1	0	1	2	1	
5	2	1	2	1	0	3	2	
6	2	3	4	1	2	3	0	1
7	3	2	3	2	1	2	1	0

Figures 1 and 2, respectively. These figures show some of the characteristics and advantages of the presented model with variable number of cells.

As can be seen, for the model with optimal number of cells, two cells in each period are formed that reduces the forming cell cost in comparison with the previous model where forming three cells had been predetermined by system designer. Also, in the first period, one quantity of machine types 1, 2, 3, and 4 and two quantities of machine type 5, six machines in total, are purchased. In the second period, it is not required to purchase new machines and to increase the available machine capacity. In the first period, machine types 4, 5, and 1 are assigned to cell 1 and in locations 1, 4, and 7, respectively. Furthermore, in the first period machine types 5, 2, and 3 are assigned to cell 2 and in locations 2, 5, and 8, respectively. In the second period, the locations of machines will be unchanged, but the configuration of cells will be changed as machine type 4 (M4) assigned to cell 1 and located in location 1 (L1) in period 1 will be assigned to cell 2 in period 2 and in a similar way machine M3 assigned to cell 2 and located in L8 in period 1 will be assigned to cell 1 in period 2. As a result, relocating machines is not necessary between two successive periods. Since there is no machine relocation between periods, the only cost which is incurred for relocation is related to installing new purchased machines in the first period.

In addition, Figure 2 shows a further illustration of the material flows between the machines represented by directed arcs. For instance, in period 1 the quantity of the first operation of part 2 processed on machine 4 in location 1 of cell 1 is 484 units, from which 199 parts are processed by operations 2 and 3 on the machine 5 in location 4 of cell 1, and the remaining 285 units are processed by operation 3 on the machine 1 in location 7 of cell 2. By considering the material flows of part 1 in period 1, all operations of part 1 are processed in location L8, so neither inter-cell and intra-cell material handling costs are incurred.

Comparing material flows between Figures 1 and 2 illustrates that the process plan for parts has been completely changed. This result shows that changing in the



number of formed cells can dramatically influence on the processing plan of parts.

Here, the objective function value (OFV) obtained in this paper is compared to the previous study (Kia et al. 2012). In order to compare two mathematical models, they should have the same components. Therefore, the costs of forming cells should be added to the OFV of the previous study. The optimal OFV and cost components for this example obtained by the previous study with three cells and presented model with 2 cells (i.e., the optimal number of formed cells) are presented in Tables 5 and 6, respectively.

As in the previous study, the number of cells which should be formed is predetermined to 3, then the cost for forming three cells in two periods is equal to $3 \times 2 \times 20,000 = 120,000$. However, in the proposed model, the number of formed cells is a decision variable and the model tries to find the optimal number of cells. The optimal number of cells formed in each period is equal to 2 which results in forming cell cost equal to $2 \times 2 \times 20,000 = 80,000$. By comparing the forming cell cost component of two models, it can be understood the presented model reduces the forming cell cost by finding the optimal number of formed cells. This reduction is equal to $120,000 -$

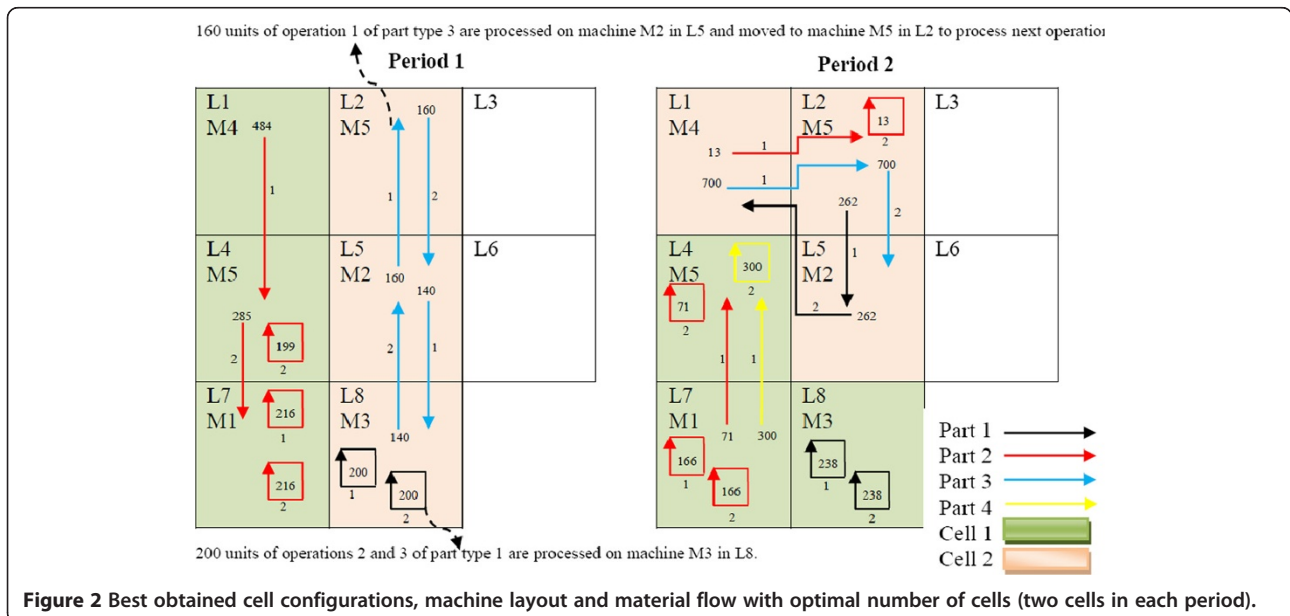


Figure 2 Best obtained cell configurations, machine layout and material flow with optimal number of cells (two cells in each period).

Table 5 Optimal OFV and cost components for the example with three cells

OFV	Intra-cell movement	Inter-cell movement	Machine relocation	Purchasing machine	Machine overhead	Processing machine	Forming cell
307,904.1	13,800	0	3,700	114,000	21,300	35,104.1	120,000

80,000 = 40,000 (i.e., $(40,000 / 252,812.7) \times 100 = 15\%$), which is a promising result. In addition, in the optimal solution of the presented model, six machines are purchased in the first period and remained for the next period. But in the optimal solution of the previous model, seven machines are purchased and utilized in two successive periods. Purchasing fewer machines results in reduction of costs of purchasing machines and machine overhead. This reduction is equal to $(114,000 + 21,300) - (94,000 - 18,800) = 225,000$ (i.e., $(22,500 / 252,812.7) \times 100 = 9\%$), which shows another advantage of the presented model capable to reduce the total costs of forming cells, purchasing machines, and machine overhead by forming cells in optimal numbers. As a result of these reductions in the components of OFV, there is a total reduction in the OFV obtained by the presented model equal to $(307,904.1 - 252,812.7) = 55,091.4$ (i.e., $(56,591.4 / 252,812.7) \times 100 = 22\%$). Even in the case without considering the forming cell cost, the model can reduce the OFV as $187,904.1 - 172,812.7 = 15,091.4$ (i.e., $15,091.4 / 172,812.7 = 9\%$), which is a remarkable improvement for such an NP hard problem.

One disadvantage seen in the previous model with the predetermined number of cells is attending of unutilized machines in cells. This situation happens in the solved example with the predetermined number of cells, in which M1 in L7 of cell 3 is presented at the second period in spite of it is not utilized. Actually, M1 is assigned to cell 3 just to satisfy the constraint of the lower bound of the cell size. If the previous model had been capable to find the optimal number of cells, it would not have formed cell 3 and would have assigned M1 in L7 to cell 2 to reduce the forming cell cost.

Finally, it can be understood that considering the number of formed cells as a decision variable and finding the optimal number of cells which should be formed in each period enable the model to reduce costs up to 22% in a small-sized numerical example. It is obvious that in large-sized problems, predetermining the number of cells by system designer can even prevent the model to find optimal strategy in forming cells and reach minimum costs. This numerical example clarifies that considering variable number of cells brings flexibility for the model to form cells more economically.

Comparing cell configurations in two periods obtained by the proposed model with two optimal cells and the previous study with 3 cells shows that the proposed model can handle varying demands by undergoing less cell re-configuration. This is another advantage of the proposed model with variable number of cells.

At the following two other numerical examples, three periods are presented to illustrate more the effect of variability in the number of formed cells on the performance of the developed model. The main difference between these examples and the first one is that those later examples contain three planning periods. The data related to the part demand in three periods for the second example is given in Table 7. Tables 8 and 9 show the cell configurations and the objective function value obtained for the second example, respectively.

As part demand increases in three periods, the number of purchased machines and formed cells are increased to enhance process capacity due to meet the increased part demands. As can be seen, the number of formed cells in successive periods is 1, 2, and 3. In the first period, one duplicate of machines of types 1, 3, and 5 is purchased, assigned to cell 1, and located in locations 6, 4, and 5, respectively. In the second period, one duplicate of machines of types 2, 4, and 5 is purchased and added to cells. Finally, in the third period, one duplicate of machines of types 1 and 5 is purchased. Average utilizations of machine time capacity in periods 1, 2, and 3 are 52%, 75%, and 93%, respectively. As it is expected, by increasing part demands, the machine utilization is heightened.

Part-related costs consist of intra-cell and inter-cell material handling costs. In addition, machine-related costs include costs of relocation, purchasing, overhead, and processing. If the number of formed cells had not been allowed to be changed in each period, three cells should have been formed. This could have totally led to forming nine cells in three periods and enforced forming cell cost as equal as $3 \times 3 \times 20,000 = 180,000$. Therefore, the OFV would have been increased up to 452,261 (i.e., $(452,261 - 392,261) / 392,261 = 15\%$). To conclude, forming cells in changeable numbers makes the model enable to reduce the forming cell costs and the OFV.

Table 6 Optimal OFV and cost components for the example with two cells

OFV	Intra-cell movement	Inter-cell movement	Machine relocation	Purchasing machine	Machine overhead	Processing machine	Forming cell
252,812.7	19,695	0	2,350	94,000	18,800	37,967.7	80,000

Table 7 Part demand for the second example

Period	Part			
	1	2	3	4
1	0	200	0	300
2	600	800	0	0
3	400	700	600	500

The third example is presented by incorporating a machine depot feature into the main model to keep idle machines in successive periods with completely different levels of part demands. This decreases machine overhead costs and provides empty locations to accommodate required machines and configure cells more effectively. By considering machine depot, in each period that there is surplus capacity, idle machines can be removed from the cells and transferred to the machine depot. In addition, whenever it is necessary to increase the processing time capacity of the system because of high demand volume, those machines can be returned to the cells.

To define this feature, additional decision variables should be added to the main model as follows:

N_{mt}^+ number of machine type m removed from the machine depot and returned to cells in period t

N_{mt}^- number of machine type m removed from cells and moved to the machine depot in period t

Also, constraint (4) should be modified by

$$\sum_c \sum_l W_{mlct} = \sum_c \sum_l W_{mlct-1} + N_{mt}^P + N_{mt}^+ - N_{mt}^- \quad (14)$$

Table 8 Cell configurations for the second example

Period	Formed cell	Location	Machine	
1	1	4	M3	
		5	M5	
		6	M1	
2	1	5	M5	
		7	M2	
		8	M3	
		1	M5	
	2	2	2	M1
			3	M4
			5	M3
3	1	7	M5	
		8	M2	
		1	M1	
		2	M1	
	2	3	4	M5
			3	M5
			6	M4
			6	M4

Table 9 Optimal OFV for the second example

OFV	Part-related costs	Machine-related costs	Forming cell costs
392,261	54,650	217,611	120,000

In addition, Constraint (15) needs to be added to the main model.

$$N_{mt}^+ \leq \sum_{t=2}^{t-1} N_{mt}^- - \sum_{t=3}^{t-1} N_{mt}^+ \quad (15)$$

Equation (14) describes that the number of machine type m utilized in the period t is equal to the number of utilized machines of the same type in the previous period plus the number of new machines of the same type purchased at the beginning of the current period, plus the number of machines of the same type removed from the machine depot and returned to the cells or minus the number of machines of the same type removed from the cells and moved to the machine depot at the beginning of the current period. Inequality (15) ensures that the number of machine type m returned from the machine depot to the cells does not exceed from the number of machine type m available in the machine depot in each period. It is worth mentioning that returning machines from the machine depot to cells can be started in the third period, because before that period there is any machines in the machine depot.

Now, the third numerical example with three periods is presented to illustrate the simultaneous effect of machine depot and variable cell number on the performance of the main model. The data related to the part demand for the third example is given in Table 10. The main difference between the first and third example is that the former contains three planning periods and six locations.

Table 11 shows the cell configurations and machine assignments to the formed cells and the machine depot for three periods. Also, the objective function value is presented in Table 12. Because of a high variation in demand of four parts in three periods, cell configurations are significantly different from each other in three periods. As it can be seen, in the first period, cells 1 and 2 are formed to process the part operations. In the first period, two units of machine types 1 and 2 and one unit of machine types 3 and 4 are purchased and assigned to cells. For instance, one unit of machine types 1, 2, and 4 is assigned to cell 1 and one unit of machine types 1, 2, and 3 is assigned to cell 2. In the second period, cell 2 is eliminated to decrease manufacturing capacity of the system due to the reduced demand. In fact, one unit of machine types 1, 2, and 4 is removed from the system and transferred to the machine depot. Placing idle machines in a depot enables the model to reduce machine overhead costs, decrease the forming cell cost by closing underutilized cells, and provide empty locations to accommodate the required machines to

Table 10 Part demand for the third example

Period	Part			
	1	2	3	4
1	140	680	250	650
2	170	210	0	290
3	280	220	730	370

process new part demands. In the third period, machine types 1, 2, and 4 transferred to a machine depot in period 2 are returned to the system, and cell 2 is again formed to increase the manufacturing capacity in period 3.

The obtained solution for this example reveals the simultaneous effect of the machine depot and variable cell number on the performance of the main model. If this model is allowed to remove idle machines from the formed cells, it will eliminate machines M1, M2, and M4 from cells and keep them in the machine depot to reduce the overhead cost. In addition, keeping idle machines in a depot gives the model an opportunity to form fewer cells and reduce related cost. As a result, the cost saving attained by keeping idle machines in a depot and forming fewer cells for this example is equal to $(1,800 + 1,500 + 1,700 + 20,000 = 25,000)$. This is a reduction in the OFV as $(25,000 / 361,411.3 \times 100 = 7\%)$.

Finally, it is worth mentioning that considering the manufacturing attributes (e.g., alternative process routing, purchasing machine, duplicate machines, machine depot, lot splitting, flexible cell configuration, and varying number of formed cells) brings the flexibility for the presented model to respond to any change in the part demand and product mix.

Table 11 Cell configurations for the third example

Period	Formed cell	Location	Machine
1	1	1	M4
		4	M2
		5	M1
	2	2	M3
		3	M1
		6	M2
2	1	1	M3
		2	M2
		3	M1
	Machine depot	M1, M2, M4	
3	1	1	M3
		4	M1
		5	M2
	2	2	M2
		3	M1
		6	M4

Table 12 Optimal OFV for the third example

OFV	Part-related cost	Machine-related cost	Forming cell cost
361,411.3	59,500	201,911.3	100,000

Numerical examples for a multi-objective model by ϵ -constraint method

Now, to investigate the performance of the proposed multi-objective model, the previous numerical example presented in 'Illustrative numerical examples for the single-objective model' section is solved by the epsilon-constrained method considering the two conflicting objectives Z_1 and Z_2 simultaneously. In ϵ -constraint method, one of the objectives is considered as the main objective function and the rest of them are incorporated in the constraint part of the model, assuming bounds for them. Therefore, the problem is changed to the single-objective problem. Then this single-objective model is solved, while the bounds of the new constraints are parametrically changed and the efficient solutions of the problem are obtained.

Table 13 shows the total workload cell imbalance (Z_2) and the total cost values (Z_1) for each non-dominated solution. In addition, the comparison between the first objective Z_1 and the workload imbalances of cells in the second objective Z_2 reveals that there is a reverse relationship between objectives Z_1 and Z_2 .

A particular solution can be selected depending on the system designer's decision. The designer may either select a configuration of cells requiring lower cost and more workload cell imbalance (i.e., solution 1) in case of reduction of manufacturing cost, or the one with higher cost and lesser workload cell imbalance (i.e., solution 4) may be adopted when the workload has to be distributed evenly among the cells.

As shown in Table 13, the workloads assigned to cells are totally different in solution 1 and results in a high volume of workload imbalance among cells. However, in solution 4 the workloads are distributed among cells evenly and this results in a workload imbalance as 49.3 h. To decrease the workload cell imbalance from 800 to 49.3 h, the value of cost objective Z_1 is increased from 260,114.2 to 269,627.7 units. This result is expected because distributing workload among cells more evenly needs transferring some operations from cells with workload higher than the average to those with workload less than the average. This incurs more movements including intra and inter-cell and increases material handling costs and finally total costs.

To say another instance that can be solved optimally in a reasonable time, the fourth numerical example is designed and solved where alternative process routings are eliminated from the main model due to reduce the computational complexity. Table 14 presents four Pareto-optimal solutions obtained by ϵ -constraint method. The cost components related to purchasing machine, machine overhead,

Table 13 Pareto front obtained by ϵ -constraint method for the first example with two objective functions

Solution number	Z_1								Z_2
	OFV	Intra-cell movement	Inter-cell movement	Machine relocation	Purchasing machine	Machine overhead	Processing machine	Forming cell	Workload cell imbalance
1	260,114.2	26,600	0	4,000	94,000	18,800	36,714.2	80,000	800
2	261,068.7	25,650	0	4,650	94,000	18,800	37,968.7	80,000	680
3	264,672.8	27,250	0	6,150	94,000	18,800	38,472.8	80,000	400
4	269,627.7	24,550	9,500	3,950	94,000	18,800	38,827.7	80,000	49.3

processing machine, and forming cell are 112,000, 24,600, 29,150, and 80,000 for all four Pareto solutions, respectively. Therefore, the sum of those components equal to 245,750 is shown in Table 14.

The trade-off between the optimal values of Z_1 and Z_2 shows a reverse relation, which is similar to the result observed in the previous example. As shown in Table 14, the workloads assigned to cells are totally different in solution 1 and results in a high volume of workload imbalance among cells. However, in solution 4, the workloads have distributed among cells evenly and this results in no workload imbalance. To decrease the workload cell imbalance from 1,490 h to 0, the value of cost objective Z_1 is increased from 288,600 to 304,300 units. This result is expected because distributing workload among cells more evenly needs transferring some operations from cells with workload higher than average to those with workload less than average. That incurs more movements including intra- and inter-cellular and increases material handling costs and finally, total costs.

To the best of our knowledge, it is the first time that a multi-objective model integrating some important design features (e.g., alternative process routings, lot splitting, group layout, dynamic demands, and flexible reconfiguration in designing a CMS) is formulated. In comparison with the previous study (Kia et al. 2012), other improving features (e.g., a variable number of cells and balancing cell workload) are incorporated to the multi-objective integrated model in order to enhance its performance and reduce the total costs as shown by a numerical example in 'Illustrative numerical examples for the single-objective model' section.

Conclusion

This paper has presented a multi-objective mixed-integer nonlinear model that integrates the CF and group layout (GL) decisions in a dynamic environment. The presented model has combined a large design features introduced in the previous studies, such as alternative process routings, operation sequence, processing time, production volume of parts, purchasing machine, duplicate machines, machine capacity, lot splitting, group layout, multi-rows layout of equal area facilities, and flexible reconfiguration. Additionally, it has addressed other important design features including a variable number of cells and balancing cell workload. The effect of newly integrated design features on improving the performance of the extended model has been illustrated by two numerical examples. The obtained results were revealed that the variable number of cells could considerably improve the performance of the extended model by reducing the forming cell cost.

The extended model was capable in determining optimally the production volume of alternative processing routes of each part, the material flow happening between different machines, the cell configuration, the machine locations, the number of formed cells, and the number of purchased machines. Also, the model has been capable to distribute the workload among formed cells more evenly by scarifying other cost components, such as inter-cell material handling cost.

As it could be recognized by a huge amount of time spent to find optimal solutions for the presented examples, the presented model is NP-hardness. Hence, designing an efficient solution approach (e.g., meta-heuristics) is needed to solve large-sized problems. This is left to the future work.

Table 14 Pareto optimal front obtained by ϵ -constraint method for the fourth example

Solution number	OFV	Z_1				Other components cost	Z_2 Workload cell imbalance	Cell workload			
		Intra-cell movement	Inter-cell movement	Machine relocation	Period 1			Period 2			
					Cell 1			Cell 2	Cell 1	Cell 2	
1	288,600	24,800	11,000	7,050	245,750	1,490	1,360	770	600	1,500	
2	292,300	25,500	15,000	6,050	245,750	770	730	1,400	1,100	1,000	
3	296,250	26,200	18,000	6,300	245,750	530	850	1,280	1,000	1,100	
4	304,300	28,250	22,500	7,800	245,750	0	1,065	1,065	1,050	1,050	

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

RK carried out the literature review studies, designed the mathematical model, and drafted the manuscript. HS participated in the design of the mathematical model and performed the numerical experiments. NJ and RTM conceived of the study and participated in its design and coordination. All authors read and approved the final manuscript.

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