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An efficient approach to determine cell formation, cell layout and intracellular machine sequence in cellular manufacturing systems

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ABSTRACT

Cellular manufacturing systems (CMS) are used to improve production flexibility and efficiency. They involve the identification of part families and machine cells so that intercellular movement is minimized and the utilization of the machines within a cell is maximized. Previous research has focused mainly on cell formation problems and their variants; however, only few articles have focused on more practical and complicated problems that simultaneously consider the three critical issues in the CMS-design process, i.e., cell formation, cell layout, and intracellular machine sequence. In this study, a two-stage mathematical programming model is formulated to integrate the three critical issues with the consideration of alternative process routings, operation sequences, and production volume. Next, because of the combinatorial nature of the above model, an efficient tabu search algorithm based on a generalized similarity coefficient is proposed. Computational results from test problems show that our proposed model and solution approach are both effective and efficient. When compared to the mathematical programming approach, which takes more than 112 h (LINGO) and 1139 s (CPLEX) to solve a set of ten test instances, the proposed algorithm can produce optimal solutions for the same set of test instances in less than 12 s.

1. Introduction

Cellular manufacturing systems (CMS) involve the identification of part families and machine cells so that intercellular movement is minimized and the utilization of the machines within a cell is maximized. This cell formation process is one of the most important steps in CMS. Extensive research has been performed on cell formation problems (CFP), many of which have been developed on the basis of heuristic clustering techniques to obtain approximate solutions. Sun, Lin, and Batta (1995) presented a short-term tabu search-(TS) based algorithm for solving CFP in order to minimize the intercellular part flows, whereas Wu, Low, and Wu (2004) maximized the part flows within cells using a long-term TS-based algorithm. Chung, Wu, and Chang (2011) proposed a TS algorithm based on a similarity coefficient to solve the CFP with alternative process routings and machine reliability considerations.

Moon and Kim (1999) considered the process plans for parts and manufacturing factors such as production volume and cell size. Lee, Luong, and Abhary (1997) developed a genetic algorithm (GA) to deal with CFP by considering production volumes, alternate routings, and the process sequence, whereas Sofianopoulou (1999) developed a simulated annealing (SA) method to deal with CFP considering alternate routings and process sequences.

Furthermore, some studies considered multiple objectives in the design of CMS. Su and Hsu (1998) introduced a parallel SA algorithm to minimize the following decision objectives: (1) the total cost of machine investment and the inter and intracellular transportation costs, (2) intracellular machine-loading unbalance, and (3) intercellular machine-loading unbalance. Lei and Wu (2005) presented a Pareto-optimality-based multi-objective TS algorithm for solving the same problem.

The cell formation, cell layout, and intracellular machine sequencing are three critical steps that are required in the design of CMS. A good cell layout reduces the number of intercellular part movements; similarly, a good arrangement in machine sequencing within each cell can reduce the number of intracellular part movements. Therefore, it is observed that the decisions regarding cell and intracellular machine layouts are very critical in the design of CMS. This is even more significant when production volume is large. A few studies, Chiang and Lee (2004) and Chan, Lau, Chan, and Choy (2006), addressed problems considering both CFP and cell layout, whereas Akturk and Turkcan (2000), solved problems considering both CFP and the intracellular machine layout. Wu, Chu, Wang, and Yan (2007), Wu, Chu, Wang, and Yue (2007)

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developed a hierarchical GA to concurrently integrate cell formation and intracellular machine sequencing decisions in CMS design. The above studies considered either cell layout or intracellular machine sequencing in their problem formulation, but not both.

In contrast, research on integrating all the three critical issues in CMS design is still very limited, as can be seen in Table 1. Ahi, Aryanezhad, Ashtiani, and Makui (2009) applied the multiple attribute decision making concepts and proposed a heuristic approach to solve this integrated and complicated problem. However, practical production factors such as alternate process routing and production volume were not considered in that study. To the best of our knowledge, the study by Chan, Lau, Chan, and Lo (2008) is possibly to be the only one to integrate CFP, cell layout and intracellular machine sequencing issues and to consider practical factors including operation sequences, alternate process routing, and production volume in the problem formulation. However, only linear layout was considered in their study. Our study follows their problem scope. In addition, both linear single- and double-row layout are allowed and investigated in our study.

Although these three critical issues should be addressed simultaneously in order to reflect the reality and obtain the best results, it is difficult to formulate one single mathematical model that can provide optimal decisions for all issues in the design of CMS. Moreover, intracellular machine layout is a detailed layout planning process that starts only after the cell formation and cell layout are determined. Thus, we propose a two-stage mathematical programming model in this study. The aim of stage I is to solve CFP and cell layout problems simultaneously, whereas the primary function of stage II is to determine the machine layout (sequencing) in each cell on the basis of the cell formation determined in stage I.

It is known that both CFP and cell layout problems are NP-hard combinatorial problems (Kusiak, 1990), not to mention the problem complexity of the integrated problem being studied. Hence, it is difficult to obtain optimal solutions through mathematical programming approach for these problems within an acceptable time duration, especially for large-sized problems. Since the TS has been widely adopted in solving CFP related problems, the TS approach is employed in both stages to solve problems more effectively and efficiently.

The remainder of this study is organized as follows: Section 2 describes the problem definition including the CFP, cell layout, and intracellular machine sequencing; Section 3 presents the mathematical models; Section 4 deals with the proposed two-stage TS approach in detail; Section 5 presents the use of a numerical example to illustrate the proposed algorithm and demonstrate the effectiveness of the proposed model and methodology; Section 6 reports the computational results of the test problems; and Section 7 concludes the study.

2. Problem definition

2.1. Cell formation

A simple CFP involves the rearrangement of its rows and columns to create part families and machine cells. After the rearrangement, blocks can be observed along the diagonal of the matrix. In the matrix, any 1s outside the diagonal blocks are called “exceptional elements,” and any 0s inside the diagonal blocks are called “voids.”

When parts have more than one process route, as in the case shown in Table 2, the grouping of parts can be more effective due to the flexibility of the routes. In this case, not only the formation of part families and machine cells must be determined but also the selection of routings for each part has to be determined to achieve decision objectives. As an example, Table A1 provides the final solution to the sample problem mentioned in Table 2.

2.2. Cellular layout

Heragu and Kusiak (1988) indicated that the layout of machines (cells) is determined by the type of material-handling devices used. Among various layout types, the linear single- and double-row layouts (shown in Fig. 1) are very popular; these layouts are frequently used because of their flexibility to incorporate different material-handling facilities. The movement distance between a pair of cells, (l, l'), can be obtained by calculating the corresponding Euclidean distance, as shown in

$$D_{l,l'} = \left[(X_{l'} - X_l)^2 + (Y_{l'} - Y_l)^2\right]^{1/2}, \tag{1}$$

Table 1
Summary of related literature.

Authors	Production data		Layout		Number of cells		Solution method
	Operation sequences	Alternative process routings	Inter-cell layout	Intra-cell layout	Pre-scribed	Auto determining	
Gupta, Gupta, Kumar, and Sundaram (1996)			✓	✓	✓		GA
Lee et al. (1997)	✓	✓			✓		GA
Su and Hsu (1998)	✓		✓	✓	✓		SA
Sofianopoulou (1999)	✓	✓			✓		SA
Bazargan-Lari, Kaebernick, and Harraf (2000)	✓		✓	✓	✓		SA
Akturk and Turkcan (2000)	✓	✓		✓	✓		Heuristic
Chiang and Lee (2004)	✓		✓			✓	GA
Lei and Wu (2005)	✓		✓	✓	✓		TS
Wu, Chu, Wang, and Yan (2006)	✓		✓	✓	✓		GA
Boulif and Atif (2006)	✓				✓		GA
Chan et al. (2006)	✓		✓		✓		GA
Arkat, Saidi, and Abbasi (2007)	✓	✓			✓		SA
Wu, Chu, Wang, and Yan (2007)	✓			✓	✓		GA
Wu, Chu, Wang, and Yue (2007)	✓			✓	✓		GA
Mahdavi and Mahadevan (2008)	✓	✓			✓		Heuristic
Chan et al. (2008)	✓	✓	✓	✓	✓		GA
Ahi et al. (2009)	✓		✓	✓		✓	Heuristic
Wu, Chung, and Chang (2009)		✓				✓	SA
Chung et al. (2011)	✓	✓	✓			✓	TS
The current study (2013)	✓	✓	✓	✓		✓	TS

Table 2
Initial machine-part matrix where alternative process routings are allowed.

PN	P1			P2		P3			P4		P5		P6			P7			P8		P9		P10	
PV	150			95		130			80		120		95			135			145		100		150	
RN	R1	R2	R3	R1	R2	R1	R2	R3	R1	R2	R1	R2	R1	R2	R3	R1	R2	R3	R1	R2	R1	R2	R1	R2
M1	1[a]				1		1	1			1		1				1		1	1			1	
M2	2	2				1		2				1	2			1	2							
M3			1						1	1			3	1							1	1	2	1
M4	3	1	2													2	3	1						
M5			3	3	4			3			3	4							5	3	4			
M6		3													2	3								
M7				2		3				3				3				3			3		3	3
M8				1		2	3		2	2				2	3			2	3		2	2		2
M9					3				3			3							4	2		3		
M10					2		2				2	2			1				2					

PN: part number; PV: production volume; RN: routing number.

[a] Process sequence.

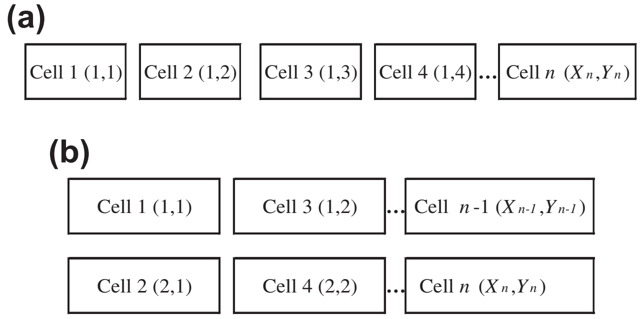


Fig. 1. Basic cellular layout type: (a) linear single-row layout (b) linear double-row layout.

where (X_l, Y_l) and $(X_{l'}, Y_{l'})$ are the coordinates of the measuring points of cells l and l'.

In reality, a few components may not be finished within only single cells. Under such circumstances, intercellular part movement will occur. For example, in Table A1, the part #9 must travel to the cell #3 for further operation on machine 5. Evidently, the different sequences of cell allocations may result in a different total intercellular movement distance (ICMD). The setting in Fig. A1a results in a total ICMD of 460. If machine cells #2 and #3 were interchanged, as shown in Fig. A1b, the total ICMD then becomes 230. Thus, the sequence of cells plays a critical role in the reduction of the total ICMD.

2.3. Intracellular machine layout

On the basis of the classification proposed by Aneke and Carrie (1986), intracellular flow can be classified into four categories: (1) repeat operation; (2) forward flows; (3) by-pass movement; and (4) reverse flows. The ideal material flow in a good layout design should mainly include consecutive forward flows (CFF). CFF usually has the benefits of smaller flow distance and easier control of the production process and material handling. Therefore, the number of CFFs within a cell is used as an index to indicate the suitability of a given machine layout.

For cell #1 in Table A1, the machine sequence is observed to be M3–M8–M7, with a total CFF of 850. If the machine sequence was changed to M8–M3–M7, the total CFF will become 0 (see Fig. A2).

Although CFF provides a method of indicating the suitability of the machine sequence within each cell, it does not consider the effects of product volumes. For example, by observing the cell #2 of Table A1, if the product volume is not considered, both machine sequences (M2–M4–M6 and M4–M2–M6) will have the same CFF of 2 (see Fig. A3). On the other hand, if the product volume is considered, the total CFF of the former is 270, whereas that of the latter is 300 (see Fig. A4). Therefore, we define a new index by considering the product volume in the proposed algorithm to guide the search for good solutions. The index would be described in detail in Section 3.2.

As illustrated above, the sequence arrangements for both the machines within each cell and the cells themselves are very important in reducing the total intracellular and intercellular part movement distance.

3. Mathematical model

In this study, we propose a two-stage mathematical programming model to integrate the cell formation, cell layout, and intracellular machine layouts problems. The aim of stage I is to simultaneously solve the cell formation and cell layout problems, whereas the primary function of stage II is to determine the machine layout in each cell on the basis of the cell formation determined in stage I. Two mathematical models are formulated (one for each stage), and they are described in Sections 3.1 and 3.2, respectively. The notations used in the model are introduced below.

Notations

Indices

a	index for operations which belongs to part i along route j ($a = 1,\ldots,K_{ij}$)
b	index for position number (or index for sequence of machine)
i	index for parts ($i = 1,\ldots,p$)
j	index for routings which belongs to part i ($j = 1,\ldots,Q_i$)
k	index for machines ($k = 1,\ldots,m$)
l	index for manufacturing cells ($l = 1,\ldots,NC$)

Input parameters

p	number of parts
Q_i	number of routings for part i
m	number of machines
r	number of routings
NC	number of cells
L_m	minimum number of machines in each cell
U_m	maximum number of machines in each cell
a_{ki}	1, if part i is processed on machine k; 0, otherwise
$D_{l,l'}$	distance between cell l and l'
$f_{kk'}$	flow coefficient between machines k and k'

K_{ij}	number of operations in routing j of part i
r_i	best routing selection for part i
M_l	set of machines in the lth cell
m_l	number of machines in cell l
N_{cff}	total number of consecutive forward flows in all the cell
N_{tf}	total number of flows
$S_{kk'i}$	unit flow coefficient for a part i between machines k and k'. $S_{kk'i} = 1$, if part i visits machines k and k' in immediate succession; otherwise $S_{kk'i} = 0$
$u_{ij}^{(a)}$	index for machines which belongs to the a-th operation of part i along route j
V_i	production volume for part i
Decision variables	
X_{il}	1, if part i locates in cell l; 0, otherwise
$X_{ijklk'l'}$	1, if routing j of part i is selected, machine k locates in cell l, and machine k' locate in cell l'; 0, otherwise
X_{lbk}	1, if machine k locates in the b-th position of cell l; 0, otherwise
Y_{kl}	1, if machine k locates in cell l; 0, otherwise
Z_{ij}	1, if routing j of part i selected; 0, otherwise

3.1. Stage I: Cell formation and cell layout

A 0–1 integer programming model is formulated below.

$$\text{Min} \quad ICMD = \sum_{i=1}^{p}\sum_{j=1}^{Q_i}\sum_{a=1}^{K_{ij}-1}\sum_{l=1}^{NC}\sum_{l'=1}^{NC} Z_{ij} Y_{(u_{ij}^{(a)})l} Y_{(u_{ij}^{(a+1)})l'} V_i D_{l,l'} \tag{2}$$

Subject to

$$\sum_{j=1}^{Q_i} Z_{ij} = 1, \quad \forall\ i \tag{3}$$

$$L_m \leqslant \sum_{k=1}^{m} Y_{kl} \leqslant U_m, \quad \forall\ l \tag{4}$$

$$\sum_{l=1}^{NC} Y_{kl} = 1, \quad \forall\ k \tag{5}$$

$$Y_{kl},\ Z_{ij} \in \{0,1\}, \quad \forall\ i,j,k,l \tag{6}$$

In the above model, Eq. (2) is the objective function which seeks the minimization of the total ICMD; Eq. (3) indicates that only a single process routing can be selected for each part; Eq. (4) imposes the upper and lower limits on the cell size; Eq. (5) restricts that each machine will be assigned to exactly one cell; and Eq. (6) indicates that Y_{kl} and Z_{ij} are 0–1 binary decision variables.

Obviously, the objective function is in a non-linear. A linearization approach for converting a non-linear model into linear form is employed. The transformation equation is as follows.

$$\text{Define} X_{ijklk'l'} = Z_{ij} Y_{ld} Y_{k'l'}, \tag{7}$$

the following set of linearization constraints are added to the model:

$$X_{ijklk'l'} \leqslant Z_{ij}, \quad \forall\ i,j,k,k',l,l' \tag{8}$$

$$X_{ijklk'l'} \leqslant Y_{kl}, \quad \forall\ i,j,k,k',l,l' \tag{9}$$

$$X_{ijklk'l'} \leqslant Y_{k'l'}, \quad \forall\ i,j,k,k',l,l' \tag{10}$$

$$Z_{ij} + Y_{kl} + Y_{k'l'} - X_{ijklk'l'} \leqslant 2, \quad \forall\ i,j,k,k',l,l' \tag{11}$$

$$Y_{kl}, Y_{k'l'}, Z_{ij}, X_{ijklk'l'} \leqslant\in \{0,1\} \quad \forall\ i,j,k,k',l,l' \tag{12}$$

The first three linearization constraints (Eqs. (8)–(10)) ensure that if one of the primary binary variables has a zero value, then their corresponding new variables will take a zero value as well. The last constraint (Eq. (11)) ensures that if all primary variables take unit values, then their corresponding new variables take unit values as well. The original mathematical programming model can thus be rewritten as:

$$\text{Min} \quad ICMD = \sum_{i=1}^{p}\sum_{j=1}^{Q_i}\sum_{k=1}^{K_{ij}-1}\sum_{l=1}^{NC}\sum_{l'=1}^{NC} X_{iju_{ij}^{(k)}lu_{ij}^{(k+1)}l'} V_i D_{ll'} \tag{13}$$

Subject to

Eqs. (3)–(5) and Eqs. (8)–(12)

After linearization, LP software can be used to solve this model.

3.2. Stage II: Intracellular machine layout

Mahdavi and Mahadevan (2008) developed a flow matrix on the basis of the number of consecutive forward flows (CFF) between a pair of machines and used it as the basic input to the grouping and layout problem. However, their method did not consider the effect of manufacturing volumes. A flow matrix with the concern of manufacturing volumes is thus proposed here. The flow matrix (F) is re-defined:

$$F = [f_{kk'}] = \sum_{i=1}^{p} V_i S_{kk'i}, \quad \forall\ k,k' \quad \text{and} \quad k \neq k' \tag{14}$$

Based on the above flow matrix, a CFF index (CFFI) for measuring intracellular machine layout is introduced in this section. The CFFI is defined as the ratio of total number of CFFs in all cells (N_{cff}) to the total number of flows (N_{tf}).

$$\text{CFFI} = \frac{N_{cff}}{N_{tf}} \tag{15}$$

where

$$N_{cff} = \sum_{l=1}^{NC}\sum_{b=1}^{m_l-1}\sum_{k\in M_l}\sum_{k'\in M_l} f_{kk'} X_{lbk} X_{l(b+1)k'} \quad k \neq k' \tag{16}$$

$$N_{tf} = \sum_{i=1}^{p} (K_{i(r_i)} - 1) V_i \tag{17}$$

The primary work of stage II is to determine the machine layout (sequence) in each cell so that the CFFI based on the given cell formation determined in stage I can be maximized. The model is given below.

$$\text{Max} \quad CFFI \tag{18}$$

Subject to

$$\sum_{k\in M_l} X_{lbk} = 1 \quad \forall\ l,b \tag{19}$$

$$\sum_{b=1}^{m_l} X_{lbk} = 1 \quad l, \forall\ k \in M_l \tag{20}$$

$$X_{lbk} \in \{0,1\} \quad \forall\ l,b,k \tag{21}$$

In the above model, Eq. (18) is the objective function that seeks the maximization of CFFI. Eqs. (19) and (20) ensure that each position is reserved for one machine only and each machine is assigned to exactly one position. Eq. (21) indicates that X_{lbk} is a 0–1 binary decision variable.

Due to the combinatorial nature of the above models, good heuristic approaches should be more appropriate than the exact method in terms of solution efficiency, especially for large-sized problems. Thus, a fast and effective two-stage TS approach is proposed in the next section to solve this highly complicated CMS problem.

4. Solution algorithm

TS has been successfully used to solve many problems including CFP appearing in manufacturing systems (e.g., Aljaber, Baek, & Chen, 1997; Chung et al., 2011; Lei & Wu, 2005; Sun et al., 1995; Wu et al., 2004). The main purposes of TS are to avoid the recently visited areas of the solution space and guide the search toward new and promising areas. Non-improving moves are allowed to escape from the local optima, and attributes of recently performed moves are declared to be tabu or forbidden for a number of iterations to avoid cycling. For more details about the TS methodology, refer to Glover (1990).

The solution searching process of the short-term TS usually gets trapped in local solutions. Hence, the mutation operator of GA is applied in this study for guiding the search to obtain a limited level of diversified solutions so as to increase the probability of finding the optimal or near optimal solutions. We propose a computational scheme called hybrid TS algorithm (HTSA) in which TS and the mutation operator from GA are integrated to solve the complex CMS problem being studied. Fig. 2 shows the computational scheme of HTSA.

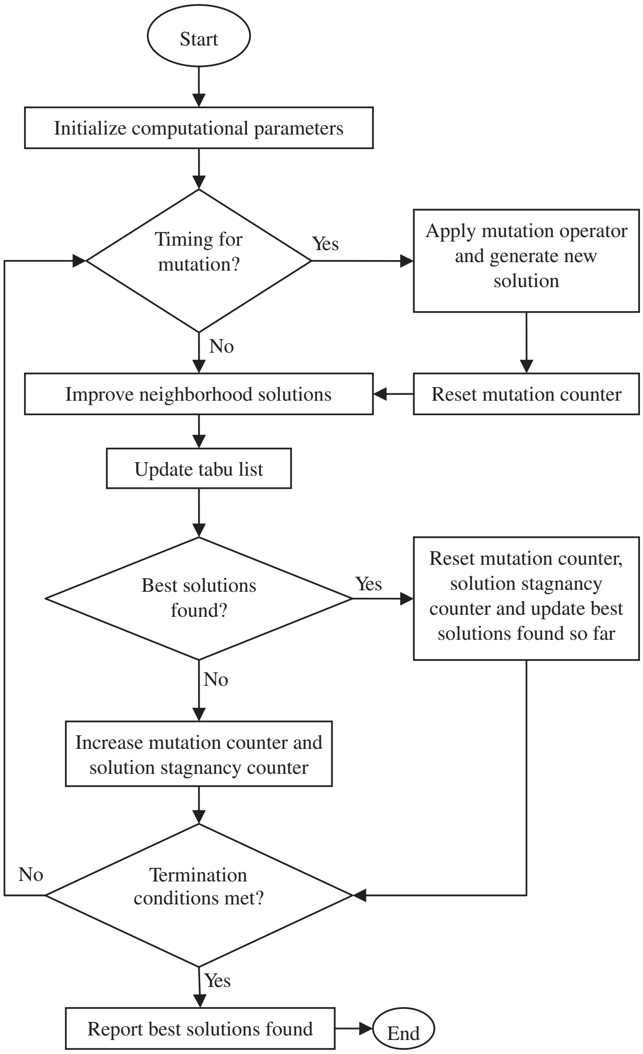

Start
Initialize computational parameters
Timing for mutation?
Yes
Apply mutation operator and generate new solution
No
Improve neighborhood solutions
Reset mutation counter
Update tabu list
Best solutions found?
Yes
Reset mutation counter, solution stagnancy counter and update best solutions found so far
No
Increase mutation counter and solution stagnancy counter
No
Termination conditions met?
Yes
Report best solutions found
End

Fig. 2. The general purpose computational scheme HTSA.

In this study, we employ HTSA as the core computational scheme and propose a fast, effective two-stage TS approach, Hybrid Tabu Search for Cell Formation (HTSCF), to obtain solutions regarding the cell formation, cell layout, and intracellular machine sequencing in the complicated CMS problem. Before proceeding to the description of HTSCF, we introduce a few notations.

N_{max}	maximum number of iterations
counter_iter	counter for number of iterations
counter_stag	counter for number of times the incumbent solution did not improve
counter_mut	counter for number of times the mutation strategy has been implemented
C^*	optimal number of cells
NC	number of cells
S^0	initial solution
S	current solution
S^N	neighborhood solution
S^*	incumbent solution of current cell size
S^{**}	best solution
$f(S)$	value of object function in solution S
N^C	set of solutions satisfying cell cardinality constraints
N^T	set of solutions in tabu status
N^A	set of solutions satisfying aspiration criterion
N^F	set of feasible solutions, $N^F = N^C - N^T + N^A$

Fig. 3 illustrates the framework of the proposed HTSCF. CFP and cell layout problem are solved in the first stage. In the second stage, the final solution obtained from stage I is used to construct an initial solution, which will be improved by our proposed algorithms to determine the layout/sequencing of machines within each cell.

4.1. Stage I: HTSCF algorithm for cell formation and cell layout

This stage consists of two procedures: the initial solution construction and the solution improvements. The improvement procedure is repeatedly applied until a cell size resulting in the minimum total ICMD has been found. The two procedures are described in detail below.

4.1.1. Initial solution construction

The initial solution is generated through a clustering algorithm. It is a composition of the following four parts: (1) selection of the layout type for cells; (2) formation of machine cells; (3) selection of routings for each part; and (4) formation of part families.

4.1.1.1. Layout type for cells. As mentioned in Section 2.2, two basic cellular layout types are considered in this study, i.e., the linear single- and double-row.

4.1.1.2. Formation of machine cells. We modify the generalized similarity coefficient method (GSCM) of Won and Kim (1997) to incorporate the product volume information. Consider a specific part-machine incidence matrix, the similarity matrix can be obtained by the formula:

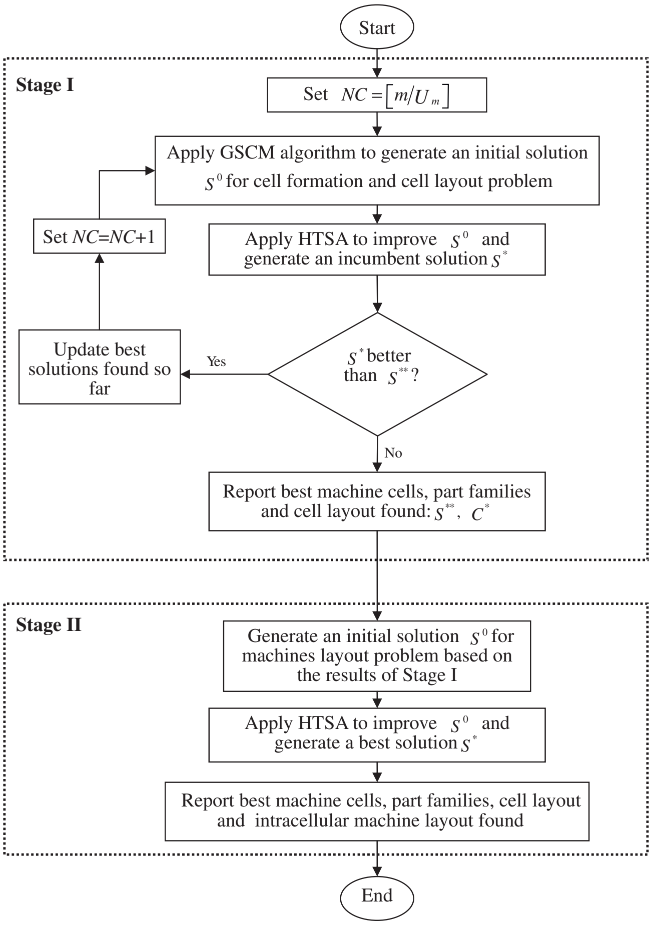

Start
Stage I
Set $NC = \lceil m/U_m \rceil$
Apply GSCM algorithm to generate an initial solution S^0 for cell formation and cell layout problem
Set NC=NC+1
Apply HTSA to improve S^0 and generate an incumbent solution S^*
Update best solutions found so far
Yes
S^* better than S^{**}?
No
Report best machine cells, part families and cell layout found: S^{**}, C^*
Stage II
Generate an initial solution S^0 for machines layout problem based on the results of Stage I
Apply HTSA to improve S^0 and generate a best solution S^*
Report best machine cells, part families, cell layout and intracellular machine layout found
End

Fig. 3. Flowchart for solution procedure of HTSCF.

$$S_{ij} = \frac{N_{ij}}{N_i + N_j - N_{ij}}, \tag{22}$$

where S_{ij} = similarity coefficient between machines i and j

$$N_i = \sum_{k=1}^{p} V_k a_i^k, N_j = \sum_{k=1}^{p} V_k a_j^k, N_{ij} = \sum_{k=1}^{p} V_k a_{ij}^k$$

p = number of parts; V_k = production volume of part k

$$a_i^k = \begin{cases} 1 & \text{if } i \in \text{some routing of part } k \\ 0 & \text{otherwise} \end{cases}$$

$$a_j^k = \begin{cases} 1 & \text{if } j \in \text{some routing of part } k \\ 0 & \text{otherwise} \end{cases}$$

$$a_{ij}^k = \begin{cases} 1 & \text{if } i,\ j \in \text{the same routing of part } k \ \text{ synchronously} \\ 0 & \text{otherwise} \end{cases}$$

After calculating the similarity matrix for each pair of machines, the initial machine assignment is generated using the single linkage clustering (SLC) algorithm. The SLC algorithm works as follows.

Step 1. Join the two most similar objects (two machines, a machine and a machine group or two machine groups) to form a new machine group.
Step 2. Evaluate the similarity coefficient between the new machine group and other remaining machine groups as follows: S_{tv} = Max{S_{ij}} $i \in t$, $j \in v$, where i is the machine in machine group t, and j is the machine in machine group v.
Step 3. Repeat Steps 1–2 until a pre-determined number of machine groups has been formed.

4.1.1.3. Selection of routings for each part. After the formation of machine cells, the routing for each part can be determined by the following procedure.

Step 1. Read the results of the machine cells formed.
Step 2. For each part with alternative routings, find the routing that will result in the least sum of ICMD. If a tie occurs, make a random selection.
Step 3. Repeat *Step 2* until the process routing has been determined for each part.

4.1.1.4. Formation of part families. After the machine cells and the routing have been determined, the assignment procedure proposed by Wu, Chang, and Chung (2008) is modified in this study to assign parts to cells. The procedure is summarized as follows:

Step 1. Read the results of machine assignment and routing selection for each part.
Step 2. For each part, find the cell to which a part assignment will result in the least sum of exceptional elements and voids. If a tie occurs, assign the part to a cell with the least number of voids.
Step 3. Repeat *Step 2* until all parts have been assigned to the cells.

Up to this point, a complete initial solution has been constructed and ready for later improvement.

4.1.2. Solution improvements

The initial solution generated in Section 4.1.1 will be improved iteratively through the proposed computational scheme HTSA to produce good solutions. Next, we describe our implementation of HTSA.

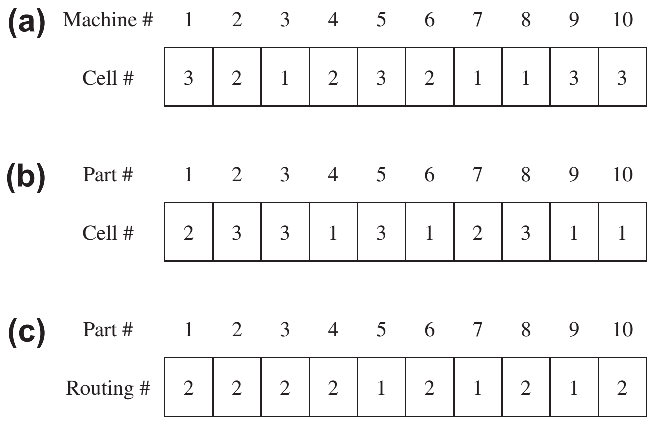
4.1.2.1. Configuration. An easy way to represent a configuration of a feasible solution for the CFP is through the usage of a string. For example, Fig. 4 is the configurations for machine cells, part families and routings. In such a configuration, the string (3, 2, 1, 2, 3, 2, 1, 1, 3, 3) in Fig. 4a represents that machines 3, 7, and 8 are assigned to cell 1; the string (2, 3, 3, 1, 3, 1, 2, 3, 1, 1) in Fig. 4b represents that parts 4, 6, 9, and 10 are assigned to cell 1; the string (2, 2, 2, 2, 1, 2, 1, 2, 1, 2) in Fig. 4c represents that parts 5, 7, and 9 each select routing #1 from their corresponding alternative routings.

4.1.2.2. Neighborhood solution searching. The neighborhood solutions (N^F) are defined as the set of all feasible solutions reachable by an insertion-move, an operation that moves a machine j from its current cell i to a new cell i'. The new move is denoted as (i',j). For the insertion-move, a move that results in the most improvement in the ICMD value from the current solution is selected, that is,

$$Z(i',j) = Max\{obj^{(i',j)} - obj^{(i,j)}, \quad \forall\ i, i', i \neq i', \quad \forall\ j \in M\},$$

where $obj^{(i,j)}$ is the objective function value; M is the set for machines.

4.1.2.3. Tabu list. In this study, a tabu list with a three-dimensional array (TL[m][NC][NC]) is used to check if a machine moving from its current cell to a new cell is forbidden or allowed, where m is the number of machines and NC is the number of cells. If machine j moves from its current cell i to a new cell i', then moving machine j from cell i' to cell i will be forbidden for a certain number of iterations, which is equal to the tabu list size (tls) (i.e., TL[j][i'][i] = tls).



(a)

Machine #	1	2	3	4	5	6	7	8	9	10
Cell #	3	2	1	2	3	2	1	1	3	3

(b)

Part #	1	2	3	4	5	6	7	8	9	10
Cell #	2	3	3	1	3	1	2	3	1	1

(c)

Part #	1	2	3	4	5	6	7	8	9	10
Routing #	2	2	2	2	1	2	1	2	1	2

Fig. 4. An example of configuration of a feasible solution to the CFP: (a) machine cells; (b) part families; (c) part routing.

4.1.2.4. Aspiration criterion. The tabu restriction may be overridden if the move will result in a solution that is better than the best solution found thus far. This aspiration criterion is applied in the proposed HTSCF algorithm.

4.1.2.5. Mutation operator. The mutation operator from the GA can provide a higher degree of diversification in the solution searching process. In this study, when the number of moves has not been improved within a certain number of iterations (*mut_check*), the machine mutation strategy is implemented by reassigning a machine to any cell other than the current one based on a prescribed probability β.

4.1.2.6. Stopping criterion. The proposed solution procedure will be terminated if a maximum number of iterations ($N_{\max}$) have been reached or if the solution has not been improved within a certain number of iterations (*stag_check*).

Initially, the number of cells is set at the nearest integer that is greater than m/U_m; it gradually increases by increments of 1 as long as solution improvement is observed. Every time the number of cells is increased, another initial solutions and HTSA improvement procedure will be started. If larger cell sizes are considered, the incumbent solution (S^*) of the current cell size is compared with the best solution (S^{**}) found thus far to determine whether to increase the cell size by 1 and restart another HTSA procedure to continue the search or to report the best solution found and terminate the solution.

Determining the proper number of cells is a difficult decision in the cell formation stage because the layout designer does not have any knowledge regarding the cell size at the beginning. Unlike many studies in the literature where the number of cells to be formed is prescribed beforehand, the number of cells resulting in the least total ICMD is automatically calculated and used in the proposed HTSCF algorithm. However, to preserve flexibility, users are allowed to specify the preferred number of cells when implementing the algorithm.

4.2. Stage II: HTSCF algorithm for intracellular machine layout

In this stage, based on the results of cell formation and cell layout from stage I, the HTSCF is used to determine the machine layout in each cell so that the CFFI can be maximized.

4.2.1. Configuration

A string is used to represent a configuration of a feasible solution of the sequences of machines within each cell. The *j*th bit of the string stores the identifier of the machine assigned to the *j*th sequence of the cell.

4.2.2. Initial solution construction

The initial solution can be generated by the following procedure:

Step 1. Read the machine cells determined in stage I.
Step 2. Order the machine cells by the cell number in an ascending order.
Step 3. Arrange the sequences of machines in each cell randomly.

4.2.3. Neighborhood solution searching

In this stage, the neighborhood of a given solution is defined as the set of all feasible solutions reachable by an exchange-move, an operation that exchanges any pair of machines within the same cell. If we exchange machine *i* with machine *j*, then the new move is denoted as (*i*,*j*). For the exchange-move, a move that results in the most improvement in the CFFI value from the current solution is selected, that is,

$$Z(i,j) = Max\{obj^{(i,j)} - obj^{(j,i)}, \quad \forall\ i,j \in M^l, i \neq j\},$$

where $M^l$is the set for machinesin cell l.

4.2.4. Tabu list

In this stage, a two-dimensional array ($m \times m$) TL[m][m] is used as a tabu list to check if a move from a solution to its neighborhood is forbidden or allowed, where m is the number of machines. If a pair of machines *i* and *j* are exchanged, then the exchanging of machine *j* and *i* will be forbidden for a certain number of iterations, which is equal to the tabu list size *tls* (i.e., TL[*j*][*i*] = *tls*).

4.2.5. Mutation strategy

When the number of moves has not been improved within a certain number of iterations (*mut_check*), the mutation strategy is implemented by exchanging any pair of machines within the same cell based on a prescribed probability β.

5. An illustrative example

In this section, the proposed approach is applied to a numerical example for illustrational purposes. The production data are shown in Table 2, which consists of 10 machines, 10 parts, and 24 process routings. The maximum number of machines in each cell is limited to 4. A linear single-row layout is assumed. The implementation of the proposed HTSCF is described as follows:

(1) Determining the layout of cells

Calculate the initial number of cells, $NC = \lceil 10/4 \rceil = 3$, and then, arrange the cells in a linear single-row cellular layout.

(2) Assigning machines to cells

The corresponding similarity matrix for machines can be obtained using Eq. (12), and it is listed in Table A2. Three cells are formed initially: machines 3, 7, and 8 are assigned to cell #1, machines 2, 4, and 6 are assigned to cell #2, and machines 1, 5, 9, and 10 are assigned to cell #3, as shown in Table 3.

(3) Selecting routings for each part

It is observed in Table 3 that parts 1, 2, 4, 6, 8, and 10 select routing #2 from their corresponding alternative routings, whereas

Table 3
Formation of machine cells for numerical example.

PN	P1			P2		P3			P4		P5		P6			P7			P8		P9		P10	
PV	150			95		130			80		120		95			135			145		100		150	
RN	R1	R2	R3	R1	R2	R1	R2	R3	R1	R2	R1	R2	R1	R2	R3	R1	R2	R3	R1	R2	R1	R2	R1	R2
M3			1						1	1			3	1							1	1	2	1
M7				2		3				3				3				3			3		3	3
M8				1		2	3		2	2				2	3			2	3		2	2		2
M2	2	2				1		2				1	2			1	2							
M4	3	1	2													2	3	1						
M6		3													2	3								
M1	1				1		1	1			1		1				1		1	1			1	
M5			3	3	4			3			3	4							5	3	4			
M9					3				3			3							4	2		3		
M10					2		2				2	2			1				2					
Inter-cell move distances (ICMD) resulted in by each part																								
ICMD	150	0	300	190	0	130	260	260	160	0	0	120	190	0	190	0	135	135	580	0	200	200	300	0

Table 4
Part routing assignment for numerical example.

Cell no.	PN	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
	PV	150	95	130	80	120	95	135	145	100	150
	RN	R2	R2	R1	R2	R1	R2	R1	R2	R1	R2
	M3				1		1			1	1
1	M7			3	3		3			3	3
	M8			2	2		2			2	2
	M2	2		1				1			
2	M4	1						2			
	M6	3						3			
	M1		1			1			1		
3	M5		4			3			3	4	
	M9		3						2		
	M10		2			2					
Inter-cell move distances (ICMD) resulted in by each part											
ICMD		0	0	130	0	0	0	0	0	200	0
Sum of voids and exceptional elements											
Cell #1		6	7	2	0	6	0	6	6	1	0
Cell #2		0	7	4	6	6	6	0	6	7	6
Cell #3		7	0	7	7	1	7	7	0	6	7

parts 3, 5, 7, and 9 select routing #1 from their corresponding alternative routings. Table 3 is thus rearranged as Table 4.

(4) Forming part families

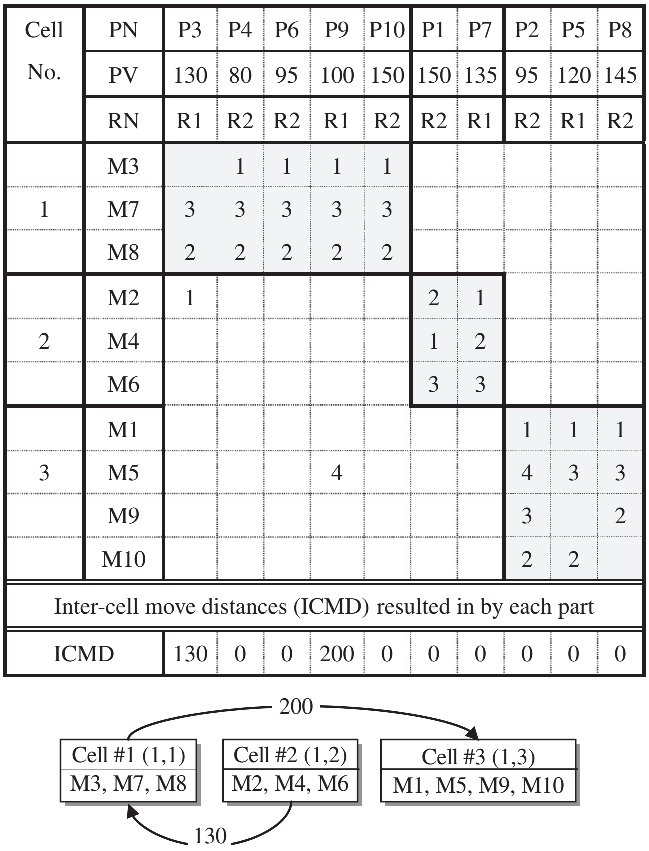
After calculating the sum of voids and exceptional elements for each part-cell combination, it is observed in Table 4 that parts 3, 4, 6, 9, and 10 are assigned to cell #1; parts 1 and 7 are assigned to cell #2; and parts 2, 5, and 8 are assigned to cell #3 because this arrangement will result in the least sum of voids and exceptional elements. Thus, the initial machine-part incidence matrix is generated with a total ICMD of 330, as shown in Fig. 5.

(5) Cell layout improvement (improve ICMD by using HTSA)

After applying the proposed HTSA in stage I, the initial solution generated is improved by exchanging the sequences of the first two cells, and thus, it results in a total ICMD of 230 in the final solution (shown in Fig. 6). So far, the cells have been formed, and the cell layout has been determined. The solution for the machine layout of each cell is determined in the next step.

(6) Machine sequencing improvement (Improve CFFI by using HTSA)

The initial machine sequences within each cell (Cell #1: M2–M4–M6, Cell #2: M3–M7–M8, and Cell #3: M1–M5–M9–M10) are determined by using the procedure described in section 4.2.2, and the initial CFFI, 10.4% [=(270/2595) × 100] can be calculated from Eq. (8). After applying the proposed HTSA in stage II, CFFI is improved to 70.52% [=(1830/2595) × 100] as the final solution. Fig. 7 shows the final configuration for the cell formation, cell layout, and intracellular machine sequences.

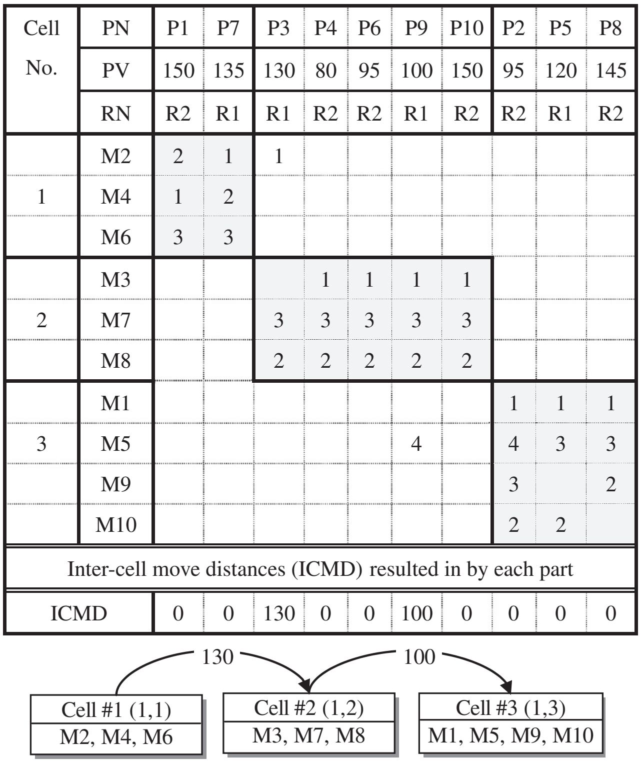


Cell No.	PN	P3	P4	P6	P9	P10	P1	P7	P2	P5	P8
	PV	130	80	95	100	150	150	135	95	120	145
	RN	R1	R2	R2	R1	R2	R2	R1	R2	R1	R2
	M3		1	1	1	1					
1	M7	3	3	3	3	3					
	M8	2	2	2	2	2					
	M2	1					2	1			
2	M4						1	2			
	M6						3	3			
	M1								1	1	1
3	M5				4				4	3	3
	M9								3		2
	M10								2	2	
Inter-cell move distances (ICMD) resulted in by each part											
ICMD		130	0	0	200	0	0	0	0	0	0

Fig. 5. Initial solution of stage I (cell formation and cell layout).

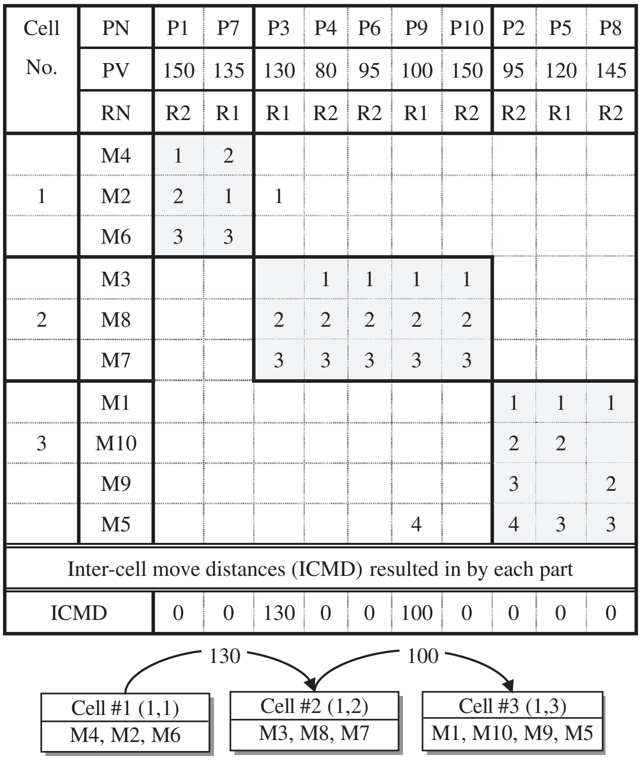
6. Computational results and comparisons

Ten test instances from the literature are used to evaluate the computational characteristics of the proposed HTSCF, and the corresponding problem descriptions are given in Table 5. The first six instances consider unique process routings, whereas the remaining four instances consider alternative process routings. The problem



Cell No.	PN	P1	P7	P3	P4	P6	P9	P10	P2	P5	P8
	PV	150	135	130	80	95	100	150	95	120	145
	RN	R2	R1	R1	R2	R2	R1	R2	R2	R1	R2
1	M2	2	1	1							
	M4	1	2								
	M6	3	3								
2	M3				1	1	1	1			
	M7			3	3	3	3	3			
	M8			2	2	2	2	2			
3	M1								1	1	1
	M5						4		4	3	3
	M9								3		2
	M10								2	2	
Inter-cell move distances (ICMD) resulted in by each part											
ICMD		0	0	130	0	0	100	0	0	0	0

Fig. 6. Final solution of stage I (cell formation and cell layout).



Cell No.	PN	P1	P7	P3	P4	P6	P9	P10	P2	P5	P8
	PV	150	135	130	80	95	100	150	95	120	145
	RN	R2	R1	R1	R2	R2	R1	R2	R2	R1	R2
1	M4	1	2								
	M2	2	1	1							
	M6	3	3								
2	M3				1	1	1	1			
	M8			2	2	2	2	2			
	M7			3	3	3	3	3			
3	M1								1	1	1
	M10								2	2	
	M9								3		2
	M5						4		4	3	3
Inter-cell move distances (ICMD) resulted in by each part											
ICMD		0	0	130	0	0	100	0	0	0	0

Fig. 7. Final solution of stage II (cell formation, cell and intracellular machine layout).

Table 5
Test instances from the literature.

Instance	Source	Size ($m \times p \times r$)	L_m	U_m
1	Nair and Narendran (1998)	8 × 20 × 20	2	4
2	Vakharia and Wemmerlov (1990)	12 × 19 × 19	2	4
3	Su and Hsu (1998)	18 × 35 × 35	2	6
4	Harhalakis, Nagi, and Proth (1990)	20 × 20 × 20	2	5
5	Nagi, Harhalakis, and Proth (1990)	20 × 51 × 51	2	5
6	Nair and Narendran (1998)	25 × 40 × 40	2	4
7	Sofianopoulou (1999)	12 × 20 × 26	2	5
8	Sofianopoulou (1999)	14 × 20 × 45	2	5
9	Sofianopoulou (1999)	18 × 30 × 59	2	7
10	Kazerooni, Luong, and Abhary (1997)	17 × 30 × 63	2	5

Table 6
Levels for TS parameters in HTSCF.

Parameter	Level 1	Level 2	Level 3	Level 4
$N_{\max}$	1000	5000	9000	13,000
tls	0	7	14	21
β	0.4	0.6	0.8	1

Table 7
Results of experimental analysis on all parameter combinations.

β	*tls*	$N_{\max}$							
		1000		5000		9000		13,000	
		Ratio	CPU (s)	Ratio	CPU (s)	Ratio	CPU (s)	Ratio	CPU (s)
0.4	0	1.0575	0.2363	1.0122	0.7694	1.0130	1.4600	1.0096	1.9350
	7	1.0250	0.2362	1.0149	0.7762	1.0044	1.3569	1.0044	2.0062
	14	1.0342	0.1837	1.0149	0.7588	1.0035	1.3419	1.0100	1.9282
	21	1.0318	0.1725	1.0120	0.7444	1.0100	1.3362	1.0000	1.8987
0.6	0	1.0259	0.1756	1.0122	0.7363	1.0008	1.3043	1.0065	1.9675
	7	1.0416	0.1688	1.0056	0.7375	1.0008	1.3212	1.0000	1.9062
	14	1.0122	0.1688	1.0065	0.7781	1.0000	1.3212	1.0000	1.8725
	21	1.0221	0.1813	1.0091	0.7844	1.0000	1.3612	1.0008	1.9950
0.8	0	1.0387	0.1793	1.0017	0.7606	1.0000	1.3749	1.0009	1.7956
	7	1.0163	0.1768	**1.0000**	**0.7187**	1.0000	1.3313	1.0000	1.8362
	14	1.0206	0.1806	1.0130	0.8112	1.0008	1.2612	1.0056	1.9106
	21	1.0206	0.1743	1.0064	0.7268	1.0008	1.2988	1.0000	1.9212
1	0	1.6630	0.1806	1.6609	0.8837	1.6630	1.4268	1.6630	2.1194
	7	1.6419	0.1768	1.6419	0.7588	1.6419	1.3187	1.6419	1.8918
	14	1.6525	0.1700	1.6510	0.7337	1.6525	1.3275	1.6538	1.8768
	21	1.6450	0.1668	1.6450	0.7400	1.6450	1.3238	1.6450	1.9012

size (machine × part × routing) of the test instances ranges from 8 × 20 × 20 to 25 × 40 × 40. The minimum number of machines in each cell is 2, while the maximum number of machines in each cell ranges from 4 to 7. The source of each test instance is given in Table 5. The production data of each test instance can also be obtained through the following link: http://sites.google.com/site/chinjuchang/data/Production_data.pdf. HTSCF is coded in C++ and implemented on an Intel(R) 2.40 GHz personal computer with 3.24 GB RAM. To obtain optimal solutions, both LINGO 14.0 and ILOG CPLEX 12.2 are used for solving the mathematical model.

6.1. Parameter settings for HTSCF

As widely known, settings of TS parameters critically affect the solution efficiency and effectiveness. An experiment regarding all the parameters in the proposed HTSCF is firstly conducted. The three TS parameters: *tls*, β, and $N_{\max}$ represent the tabu list size, prescribed probability, and maximum number of iterations, respectively. Four levels are chosen for each parameter and given in Table 6. Note that *mut_check* and *stag_check* are fixed at $m(NC-1)/2$ and $N_{\max}/3$, respectively.

Five test problems (#1, #2, #4, #6, #10) representing various problem sizes are used in the experimental analysis. Due to the

Table 8
Comparisons of computation results.

Instance	Size ($m \times p \times r$)	L_m	U_m	HTSCF (linear single-row layout)				HTSCF (linear double-row layout)				ILOG CPLEX (dynamic search)				LINGO (branch-and-bound)			
				NC	ICMD	CFFI (%)	CPU (s)	NC	ICMD	CFFI (%)	CPU (s)	NC	ICMD	CFFI (%)	CPU (s)	NC	ICMD	CFFI (%)	CPU (s)
1	8 × 20 × 20	2	4	2	**12.00**	**41.46**	0.31	2	**12.00**	**41.46**	0.38	2	12.00	41.46	0.29	2	12.00	41.46	1.00
2	12 × 19 × 19	2	4	3	45.00	41.18	0.60	3	**43.49**	**43.14**	0.65	3	43.49	43.14	0.13	3	43.49	43.14	19.00
3	18 × 35 × 35	2	6	3	5595.00	**31.98**	2.05	3	**5402.71**	**31.98**	1.74	3	5402.71	31.98	1.62	3	5402.71	31.98	172.00
4	20 × 20 × 20	2	5	5	24.00	38.98	1.21	5	**18.66**	**40.68**	1.14	5	18.66	40.68	12.79	5	18.66	40.68	7141.00
5	20 × 51 × 51	2	5	5	100.00	**34.72**	2.36	5	**89.46**	**34.72**	2.07	5	89.46	34.72	8.16	5	89.46	34.72	3747.00
6	25 × 40 × 40	2	4	7	52.00	33.33	2.04	7	**37.90**	**34.41**	2.00	7	37.90	34.41	1052.06	7	37.90	34.41	298228.00
7	12 × 20 × 26	2	5	3	2670.00	**35.18**	0.82	3	**2561.63**	**35.18**	0.63	3	2561.63	35.18	0.53	3	2561.63	35.18	20.00
8	14 × 20 × 45	2	5	3	30.00	27.69	0.83	3	**27.07**	**32.31**	0.81	3	27.07	32.31	24.41	3	27.07	32.31	58021.00
9	18 × 30 × 59	2	7	3	35.00	**24.42**	1.12	3	**33.24**	**24.42**	1.05	3	33.24	24.42	21.23	3	33.24	24.42	37183.00
10	17 × 30 × 63	2	5	4	**760.00**	**79.74**	1.22	4	**760.00**	**79.74**	1.16	4	760.00	79.74	18.16	4	760.00	79.74	1222.00

NC: number of cells; ICMD: inter-cell move distances; CFFI: consecutive forward flow index.

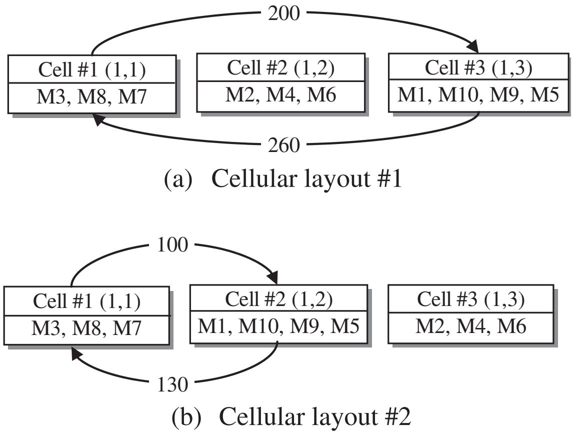


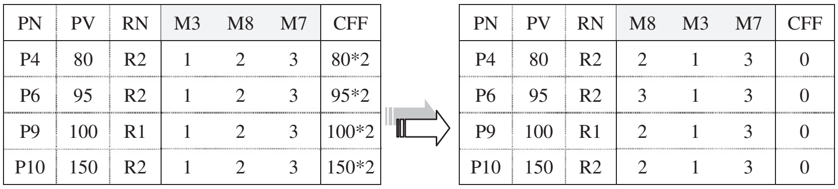
Fig. A1. Two different cell layouts.

stochastic features of the proposed method might have, five independent runs were performed on each parameter combination for each test instance. The ratios of the results from HTSCF to the solutions from exact method (branch and bound) are calculated, and the average ratios are given in Table 7. From Table 7, it can be observed that the parameter combination ($tls = 7$, $\beta = 0.8$, $N_{\max} = 5000$) works very well without consuming too much run time. We hence decide to use it as the suggested parameter setting throughout the testing runs.

6.2. Results comparison

The parameter setting suggested in Section 6.1 is used by HTSCF to run all the test instances in this section. Table 8 shows a comparison between the computational results for both the linear single- and double-row cellular layouts. The bold characters indicate the best values obtained for each test instance for the two layout types.

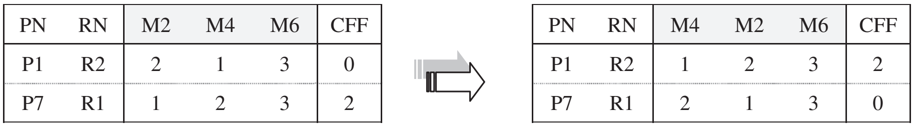
In ten test problems, the two cellular layout types produce the same results in two test problems (#1 and #10); however, the linear double-row layout produces better results than those by the linear single-row layout in the remaining eight problems (#2–#9) in terms of ICMD. Regarding CFFI, the double-row layout generates on an average slightly better values than those by the single-row layout.



PN	PV	RN	M3	M8	M7	CFF
P4	80	R2	1	2	3	80*2
P6	95	R2	1	2	3	95*2
P9	100	R1	1	2	3	100*2
P10	150	R2	1	2	3	150*2

PN	PV	RN	M8	M3	M7	CFF
P4	80	R2	2	1	3	0
P6	95	R2	3	1	3	0
P9	100	R1	2	1	3	0
P10	150	R2	2	1	3	0

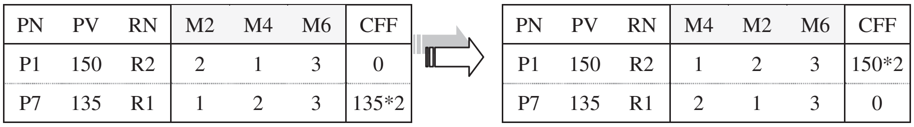
Fig. A2. CFF differences caused by different machine sequences.



PN	RN	M2	M4	M6	CFF
P1	R2	2	1	3	0
P7	R1	1	2	3	2

PN	RN	M4	M2	M6	CFF
P1	R2	1	2	3	2
P7	R1	2	1	3	0

Fig. A3. CFF information for cell #2 when product volume is not considered.



PN	PV	RN	M2	M4	M6	CFF
P1	150	R2	2	1	3	0
P7	135	R1	1	2	3	135*2

PN	PV	RN	M4	M2	M6	CFF
P1	150	R2	1	2	3	150*2
P7	135	R1	2	1	3	0

Fig. A4. CFF information for cell #2 when product volume is considered.

Table A1
Final machine-part matrix of Table 2.

Cell no.	PN	P4	P6	P9	P10	P1	P7	P2	P3	P5	P8
	PV	80	95	100	150	150	135	95	130	120	145
	RN	R2	R2	R1	R2	R2	R1	R2	R2	R1	R2
1	M3	1	1	1	1						
	M8	2	2	2	2				3		
	M7	3	3	3	3						
2	M2					2	1				
	M4					1	2				
	M6					3	3				
3	M1							1	1	1	1
	M10							2	2	2	
	M9							3			2
	M5			4				4		3	3

Table A2
Similarity matrix for machines in numerical example.

Machine	1	2	3	4	5	6	7	8	9	10
1	–									
2	0.447	–								
3	0.181	0.086	–							
4	0.279	0.452	0.211	–						
5	0.359	0.206	0.216	0.155	–					
6	0.000	0.393	0.000	0.750	0.085	–				
7	0.091	0.101	0.455	0.144	0.137	0.000	–			
8	0.164	0.091	0.394	0.125	0.327	0.078	0.844	–		
9	0.182	0.114	0.193	0.000	0.355	0.000	0.000	0.284	–	
10	0.480	0.120	0.000	0.000	0.373	0.000	0.000	0.240	0.537	–

In addition, when compared with the exact method (branch and bound), it is observed that LINGO achieves global optimum for all test instances (they are solved to optimality without setting any terminating criteria). However, for problems #6 and #8, the exact method takes 298228 s (82.84 h) and 58,021 s (16.12 h), respectively, to obtain the optimal solutions. In contrast, our proposed algorithm in the double-row layout can find the optimal solution for all test instances as well, but it takes only 2.00 and 0.81 s to solve problems #6 and #8 optimally, respectively.

It can also be observed from Table 8 that ILOG CPLEX achieves global optimum for all test instances as well. For the ten test problems, the total computational times are only 1139 s, in comparison with the 405,754 s (112.71 h) for the LINGO. However, the total run times are still much longer than the 11.63 s for our proposed algorithm HTSCF. For problems with smaller sizes, such as #1, #2, #3, and #7, the run times of CPLEX are shorter than the proposed HTSCF; however, run times increase drastically as problem sizes increase, e.g., test problem #6. These findings illustrate the superiority of our proposed algorithms in terms of both their effectiveness and efficiency.

The complete solutions for all test instances obtained by HTSCF are presented in the Appendix A (Table B1). The solutions include the cell formation plan, cellular layout, and the machine sequences within each cell.

7. Conclusion

Although extensive research has been performed on CFP, research on integrating the three critical issues in CMS design, i.e., CFP, cell layout and intracellular machine sequencing, remains very limited. In this study, a two-stage mathematical programming

Table B1
Results of test instances.

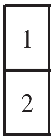
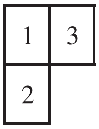
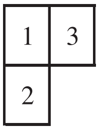
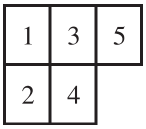
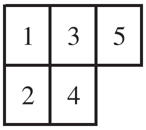
Instance no.	Cell no.	Order of machines	Set of parts	Cell layout
1	1	6, 5, 1, 3	1, 2, 5, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 19	
	2	2, 4, 7, 8	3, 4, 6, 7, 18, 20	
2	1	1, 4, 8, 9	1, 2, 3, 4, 5, 6, 7, 9, 10	
	2	3, 5, 2, 6	8, 11	
	3	7, 10, 11, 12	12, 13, 14, 15, 16, 17, 18, 19	
3	1	5, 11, 1, 15, 9, 10	4, 5, 6, 16, 17, 18, 19, 21, 28, 29, 30, 31	
	2	17, 13, 6, 4, 12, 2	1, 9, 10, 11, 12, 23, 24, 25, 34	
	3	7, 14, 3, 16, 8, 18	2, 3, 7, 8, 13, 14, 15, 20, 22, 26, 27, 32, 33, 35	
4	1	3, 2, 11, 14	2, 4, 11, 19	
	2	16, 17, 5	6, 7, 15	
	3	9, 18, 10, 1, 12	1, 9, 12, 14, 17, 20	
	4	4, 6, 7, 15, 13	5, 8, 13, 16	
	5	8, 19, 20	3, 10, 18	
5	1	9, 1, 12, 6	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	
	2	18, 7, 5, 16, 2	12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29	
	3	14, 17, 10	39, 40, 41, 42, 43, 44, 45, 46, 47, 48	
	4	8, 3, 11, 19, 20	30, 31, 32, 33, 34, 35, 36, 37, 38	
	5	4, 13, 15	49, 50, 51	

Table B1 (*continued*)

Instance no.	Cell no.	Order of machines	Set of parts	Cell layout
6	1	20, 3, 11, 25	3, 9, 13, 14, 33	1 3 5 7 2 4 6
	2	24, 17, 1, 2	2, 12, 36	
	3	9, 8, 10	10, 19, 21, 22, 28, 38	
	4	19, 5, 16, 4	8, 15, 16, 23, 24, 30, 31	
	5	21, 6, 22, 15	18, 25, 27, 29, 35, 40	
	6	23, 12, 7, 18	1, 4, 5, 6, 7, 17, 20, 26, 34, 37, 39	
	7	14, 13	11, 32	
7	1	2, 3, 4, 5, 6	1, 3, 4, 5, 6, 11, 14, 15, 16, 17, 18, 20	1 3 2
	2	8, 7, 10, 11, 12	2, 7, 9, 12, 13	
	3	1, 9	8, 10, 19	
			Set of parts (route)	
8	1	3, 2, 11, 6, 14	1(2), 2(2), 5(1), 9(2), 13(2), 15(3), 16(1), 17(1)	1 3 2
	2	13, 4, 1, 10, 7	3(4), 4(1), 8(2), 10(2), 14(1), 20(2)	
	3	9, 12, 8, 5	6(1), 7(1), 11(1), 12(1), 18(1), 19(1)	
9	1	1, 2, 14, 7, 13, 11, 15	1(1), 2(1), 4(1), 9(1), 11(1), 12(3), 15(1), 25(1), 29(1), 30(1)	1 3 2
	2	16, 12, 4, 3, 9, 10, 6	3(3), 6(3), 7(1), 10(1), 13(1), 14(1), 16(1), 17(1), 19(1), 20(1), 21(1), 22(1), 23(1), 26(1), 27(1), 28(1)	
	3	17, 8, 5, 18	5(1), 8(2), 18(1), 24(2)	
10	1	14, 7, 3, 15, 2	1(3), 9(1), 13(1), 16(1), 17(1), 18(2), 24(1), 26(2), 29(1)	1 3 2 4
	2	17, 1, 9	3(2), 12(2), 20(2), 23(1), 25(1)	
	3	11, 6, 13, 12, 10	2(1), 4(1), 5(1), 6(1), 10(4), 14(1), 15(3), 19(1), 21(1), 27(1), 28(1)	
	4	16, 8, 5, 4	7(3), 8(1), 11(1), 22(1), 30(1)	

model is formulated to integrate the three critical issues, considering problem features such as alternative process routings, operation sequences, production volume, and the cellular layout type. Because of the NP-complete nature of this complex problem, an effective two-stage TS algorithm (HTSCF) based on a generalized similarity coefficient is proposed. As in the case of the proposed mathematical formulation, the proposed HTSCF is implemented in two stages. The first stage mainly solves the cell formation and cell layout problems simultaneously in terms of the minimization of the total ICMD. In the second stage, the final solution obtained from stage I is used to construct an initial solution that is improved by our proposed algorithms to determine the layout of the machines within each cell in terms of maximizing CFFI.

Computational results from test problems show that the linear double-row layout performs better than the single-row layout in terms of reducing the total ICMD. In addition, in contrast with the exact methods, which take more than 112 h (LINGO) and 1139 s (ILOG CPLEX), respectively, to achieve global optimum in all test instances, the proposed algorithm in the double-row layout type can find the optimal solution for all test instances in only 11.63 s. It should be noted that all of the best solutions can be found within three seconds, irrespective of the problem size.

This main contributions of this study are as follows: (1) we formulate a two-stage mathematical programming model for solving the complex problem, which simultaneously integrate the three critical issues in CMS design while considering operation sequences, alternative routing, production volume and different cellular layout types; (2) we present a new performance measure, CFFI, to evaluate the goodness of the intracellular machine layout; (3) we propose a two-stage TS approach, HTSCF, to solve the complex problem being studied, and the computational results indicate the superiority of our proposed algorithms in terms of both their effectiveness and efficiency.

In this study, the total intercellular movement distance is minimized in the first stage while the number of consecutive forward flows is maximized in the second stage. Minimization of intracellular movement as well as cell load variation is not considered during the solution searching process. In addition, all the machines are assumed in perfect condition, we do not deal with machine breakdowns or reliability issues. These are the limitations of this research.

The three critical issues in CMS design are solved through a two-stage mathematical programming model and a two-stage TS approach (HTSCF) in this study. Developing a solution scheme that concurrently considers the three issues and provides optimal decisions can be attempted as future work. Other extensions of this study would be to include related issues such as parts scheduling, production resource allocation, machine reliability considerations and various cell layout types (such as U-shaped) into the current model.

Appendix A

See Figs. A1–A4 and Tables A1–B1.

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