An efficient tabu search approach to determine cell formation, cell layout, and intracellular machine layout in the cellular manufacturing system

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Abstract

Formation of manufacturing cell, determination of cell layout and intracellular machine layout are three basic steps in the design of CMS. It is important and more practical to integrate the above factors simultaneously in the design of CMS. However, very little researches have been done on CFP to integrate cell formation, cell layout, and intracellular machine layout simultaneously. Hence, we propose a two-stage approach to address these issues. Two mathematical models are developed for the first and second stage, respectively. As problems in the two stages are NP-hard, tabu search (TS) approach is employed in both stages. Several test instances from the literature are employed to illustrate the effectiveness of the proposed solution algorithm. Computational experiences from test problems show that the proposed approach is extremely effective and efficient. When compared with the mathematical programming approach which took 34 hours to solve problems, the proposed algorithm is able to produce optimal solutions in less than 1 second. These comparisons show that the proposed approach is very effective, efficient and practical.

Keywords: Cell formation; Cell layout; Intracellular machine layout; Alternative process routings; Tabu search.

1. Introduction

In response to various and diversified customer demands, companies must adopt innovative manufacturing strategies and manufacturing technologies to achieve an efficient and flexible manufacturing system. Group technology (GT) is one such approach that meets the requirements of system flexibility and product variations. Cellular manufacturing is the implementation of GT. It has been reported that the implementation of cellular manufacturing result in significant benefits such as reduced material handling costs, work-in-progress inventory, throughput and set-up times, as well as simplified scheduling, and improved quality [1].

Although cellular manufacturing may provide great benefits, the cellular manufacturing system (CMS) design is complex for real life problems. Specifically, a cell formation problem (CFP) is the crucial element in designing CMS [2]. However, it has been known that the CFP with considerations of cell formation and cell layout simultaneously are NP-hard combinational problems [3]. Hence, it is difficult to obtain optimal solutions in an acceptable length of time, especially for large-sized problems.

Many models and solution approaches have been developed to identify machine cells and part families. However, very little has been devoted to integrate cell formation, cell layout, and intracellular machine layout simultaneously with the considerations of operation sequences, alternative routing, and production volume. Formation of manufacturing cell, determination of cell layout and intracellular machine layout are three basic steps in the design of CMS. Operation sequences, alternative routing, and production volume may exist in a real CMS environment. Hence, it is important and more practical to integrate the above factors simultaneously in the design of CMS.

In this paper, we propose a two-stage approach, HTSCF, to address these issues. The first stage aims to simultaneously provide solutions pertaining to the number of cells and their respective membership of parts and machines as well as the cell layout. The second stage solves the machine layout in each cell formed in the first stage. Two mathematical models are developed for the first and the second stage, respectively. As problems in the two stages are NP-hard, TS approach is employed in both stages. Several test instances from the literature are employed to illustrate the effectiveness of the proposed solution algorithm. Encouraging results are obtained when compared with the mathematical programming approach. These comparisons show that the proposed approach is very effective and efficient.

Table 1. Summary of literature review

Authors	Decisions			Production data			Method
	CF	Inter CL	Intra CL	BD	OS	APR	
[4]	✓	✓	✓				GA
[5]	✓				✓	✓	GA
[6]	✓	✓	✓		✓		SA
[7]	✓				✓		SA
[8]	✓		✓		✓		GA
[9]	✓			✓			EA
[10]	✓	✓	✓		✓		TS
[11]	✓				✓		GA
[12]	✓	✓			✓		GA
[13]	✓	✓	✓		✓		GA
[14]	✓		✓		✓		GA
[15]	✓				✓	✓	SA
[16]	✓			✓			SA
[17]	✓				✓	✓	MP
[18]	✓	✓	✓		✓	✓	GA
[19]	✓	✓	✓		✓		Novel
[20]	✓			✓		✓	SA

CF: cell formation, BD: binary data, OS: operation sequences, APR: alternative process routings, CL: cell layout, MP: mathematical programming, EA: evolutionary approach, SA: simulated annealing, GA: genetic algorithm

2. Problem definition

2.1 Alternative process routings

When parts have alternative process routings (APR) is called the generalized CFP. Such as the case shown in Table 1, part #1 has two process routings R1 and R2. Under this circumstance, 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 such as the minimization of intercellular movement. For instance, Table 3 provides a feasible solution to the sample problem of Table 2 which has three cells with machine groupings for each cell as Cell 1: (M3, M7); Cell 2: (M2, M4, M6); and Cell 3: (M1, M5, M8).

Table 2. Initial machine-part matrix

PN	P1		P2		P3		P4		P5		P6	
PV	150		95		130		80		95		135	
RN	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
M1				2		2						
M2	2*	2			1				2		1	2
M3			1		2	3	2	2		2		
M4	3	1									2	3
M5	1			1		1			1			1
M6		3									3	
M7							1	1	3	1		
M8			2	3						3		

PN: Part Number; PV: Production Volume; RN: Routing Number; * Operation Sequences

Table 3. Final machine-part matrix of Table 1

PN	P4	P5	P1	P6	P2	P3
PV	80	95	150	135	95	130
RN	R2	R2	R2	R1	R2	R2
M7	1	1				
M3	2	2				3
M2			2	1		
M4			1	2		
M6			3	3		
M5					1	1
M1					2	2
M8		3			3	

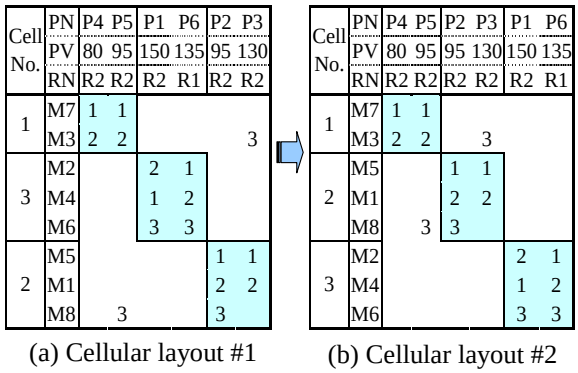
2.2 Cellular layout

In reality, some components may not be finished within only single cells; they have to travel to another cell(s) for further operation(s). Under such circumstances, intercellular part movement will take place. The corresponding inter-cell move distance (ICMD), can be obtained by calculating the corresponding Euclidean distance, as in equation (1).

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

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

Furthermore, different sequence of cells allocation may result in different total ICMD. The setting in Fiure 1(a) results in a total ICMD of 4. If machine cells #2 and #3 were interchanged, as shown in Figure 1(b), the total ICMD then becomes 2, which is only a half of that of Figure1(a). Thus, the sequence of cells does play a critical and crucial role in reducing the total ICMD.



(a) Cellular layout #1 (b) Cellular layout #2

Figure1. Different sequence of cells allocation

2.3 Intracellular machine layout

The parts being transported from one machine to another within a cell are called intra-cellular flow. The characteristics of intra-cellular part flow are that they are usually rushed and short in distances. In CMS, these movements are very frequent, and the

frequency directly affects the intracellular machine layout design. Based on the classification of Aneke and Carrie (1986)[21], the intra-cellular flow can be classified into four categories (see Figure 2): (1) Repeat operation, R; (2) Forward flows, FF; (3) By-pass movement, BP; and (4) Reverse flows, RF. The ideal material flow in a good layout design should be mostly consecutive forward flows (CFF). The CFF usually has the benefits of smaller flow distance, easier control of the production process and easier material handling (Ho et al. 1993[22]). The number of CFF within a cell was hence used as a measure to understand how appropriate a machine layout is.

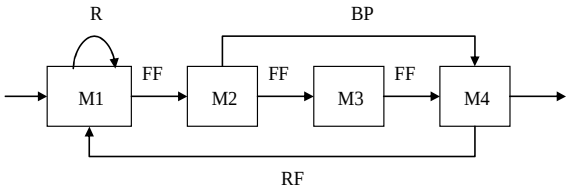


Figure 2. Intra-cellular part flow

3. Mathematical model

In this paper, a two-stage mathematical programming model is formulated to integrate cell formation, inter-cell layout, and intracellular machine layout problem with the considerations of operation sequences, alternative process routings, and production volume.

In the first stage, the cell formation, and the cell layout are jointly determined based on the minimization of total ICMD. The work in second stage is to determine the machine layout (sequence) in each cell in terms of maximizing the consecutive forward flow index (CFFI) based on the given cell formation determined in stage one. Two mathematical models are formulated, one for each stage, and are given in subsections 3.1 and 3.2, respectively. The notations used in both models are presented below.

(1). Indices:

i : Index for parts (i=1,..., p)
j : Index for routings which belongs to part i (j=1,..., Q_i)
k : Index for machines (k=1,..., m)
a : Index for operations which belongs to part i along route j (a=1,..., K_{ij})
l : Index for manufacturing cells (l=1,..., NC)

(2). Input parameters:

M : Number of machines
P : Number of parts
NC : Number of cells
V_i : Production volume for part i
Q_i : Number of routings for part i
U_m : Maximum number of machines in each cell
L_m : Minimum number of machines in each cell
$D_{l,l'}$: The Euclidean distance between cell l and l'
$u_{ij}^{(a)}$: Index for Machines which belongs to the a-th operation of part i along route j
N_{cff} : Number of consecutive forward flows in all the cell
N_{tf} : Total number of flows
r_i : Best routing selection for part i
K_{ij} : Number of operations in routing j of part i

(3). Decision variables:

Y_{kl} : 1, if machine k locates in cell l; 0, otherwise
X_{il} : 1, if part i locates in cell l; 0, otherwise
Z_{ij} : 1, if routing j of part i selected; 0, otherwise
$X_{(u_{i(r_i)}^{(k)})(u_{i(r_i)}^{(k+1)})}$: 1, if machine $u_{i(r_i)}^{(k)}$ and machine $u_{i(r_i)}^{(k+1)}$ locate in the same cell l and the difference of the sequence number $S_{u_{i(r_i)}^{(k+1)}\,l}$ and $S_{u_{i(r_i)}^{(k)}\,l}$ is equal to one, that is ($S_{u_{i(r_i)}^{(k+1)}\,l}$ - $S_{u_{i(r_i)}^{(k)}\,l}$)=1; 0, otherwise
$X_{ijkls'}$: 1, if routing j of part i is selected; machine k locates in cell l and machine s locate in cell l'; 0, otherwise

3.1 Stage I: Cell formation and cell layout

The aim of this stage is to solve the cell formation and inter-cell layout simultaneously in terms of minimization of the ICMD. A 0-1 integer programming model is given below.

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

Subject to:

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

$$L_m \le \sum_{k=1}^{m} Y_{kl} \le U_m \quad \forall l \quad (4)$$

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

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

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

3.2 Stage II: Intracellular machine layout

As mentioned in section 2.3, taking the effect of product volume into account is more realistic when designing a performance measure for intracellular

machine layout. A consecutive forward flow index (CFFI) is thus proposed for this sake. The CFFI is defined as the ratio of number of consecutive forward flows in all cells to the total number of flows.

The primary work of the second stage is to determine the machine layout (sequence) in each cell in terms of maximizing the CFFI based on the given cell formation determined in stage one. The model is given below.

$$\text{Max} \quad \text{CFFI} = \frac{N_{cff}}{N_{tf}} \tag{7}$$

where

$$N_{cff} = \sum_{i=1}^{p} \sum_{k=1}^{k_{i(r_i)}-1} X_{u_{i(r_i)}^{(k)} u_{i(r_i)}^{(k+1)}} V_i \tag{8}$$

$$N_{tf} = \sum_{i=1}^{p} (K_{i(r_i)} - 1) V_i \tag{9}$$

$$X_{u_{i(r_i)}^{(k)} u_{i(r_i)}^{(k+1)}} \in \{0,1\} \tag{10}$$

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

Tabu Search (TS) has been successfully used to solve many problems appearing in manufacturing systems including CFP (Lozano et al., 1999[23]). On the other hand, a number of similarity coefficient methods (SCM)-based approaches have been proposed, and have been shown to produce good machine-part grouping and are more flexible in incorporating various production data into the machine-part clustering process. Thus, a two-stage HGCFA merging SCM-based clustering algorithm and TS method is proposed. The framework of the proposed HGCFA is illustrated in Figure 3.

The first stage mainly solves the CF and inter-cell layout (Inter CL) problem simultaneously in terms of minimizing the sum of total ICMD. In the second stage, the final solution obtained from the first stage is used to construct an initial solution to be improved by the proposed algorithms to determine intra-cell layout (intra CL) in terms of maximizing the CFFI.

The detailed procedures of both stages are described below.

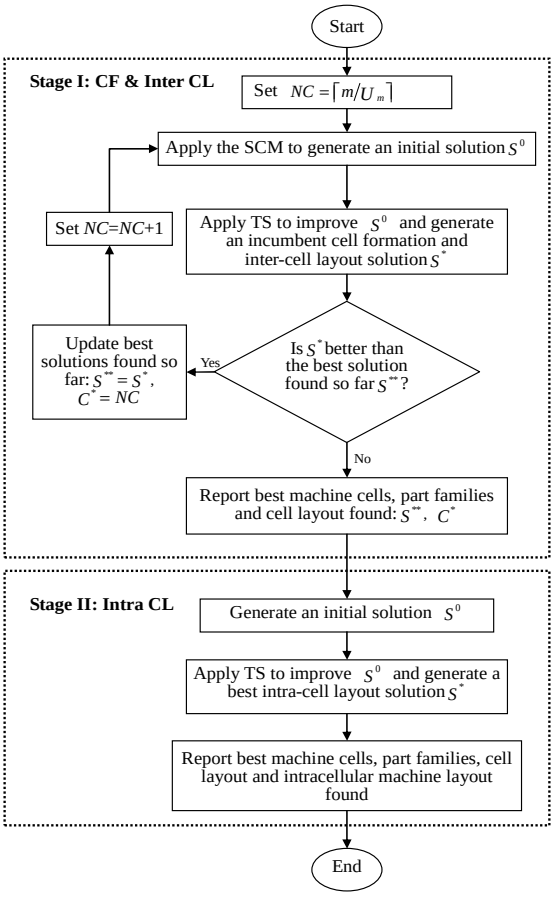


Figure 3. Framework of the proposed HGCFA

Stage I of HGCFA:

Step 1. Set $NC = \lceil m/U_m \rceil$.

Step 2. Apply SCM-based clustering algorithm to generate an initial solution S^0.

Step 3. Let $S^{**} \leftarrow S^0$.

Step 4. Apply TS procedure to improve S^0 and generate an incumbent solution S^*.

Step 5. If $f(S^*) < f(S^{**})$, then set $S^{**} \leftarrow S^*$, $C^* = NC$, $NC = NC+1$, go to Step 2; otherwise, report the best cell formation and inter-cell layout found, and terminate stage I.

Note that the algorithm in this stage consists of an initial solution and an improvement procedure that will be repeatedly applied until a cell formation resulting in the minimum of the total ICMD have been found. In Step 1, the initial number of cells, *NC*, can be easily approximated by the nearest integer that is greater than m/U_m; it gradually increases by increments of 1 as long as solution improvement is observed in Step 5. Every time the number of cells is increased, another initial solutions and TS improvement procedure will be begun in Steps 2 and 4, respectively. For a specific cell size, the best routing selection and grouping plan for parts and

machines will be calculated iteratively and obtained in Step 4. Initial solutions of machine cells, routing selections, and part families are generated in Step 2. If larger cell sizes are considered, it is possible that better solutions may be obtained. The incumbent solution (S^*) of the current cell size (NC) is thus compared with the best cell formation solution (S^{**}) found thus far in Step 5 to determine whether to increase the cell size by 1 and restart another TS procedure to continue the search or to report the best cell formation 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 most of the study in the literature where the number of cells to be formed is prescribed beforehand, the number of cells resulting in the least total cost is automatically calculated and used in the proposed approach. However, to preserve flexibility, users are allowed to specify the preferred number of cells when implementing the algorithm. For users having specific preferences in cell size, the proposed algorithm can save considerable amount of run time because it will skip the process of iteratively searching for the cell size that will result in the best objective function values. The savings in run time become even more significant as the cell size increases.

Stage II of HGCFA:

Step 1. Read solutions from stage I, including number of cells, C^* and cell formation with inter-cell layout S^{**}.

Step 2. Generate an initial solution S^0.

Step 3. Apply TS procedure to improve S^0 and generate a best layout of machines within each cell (S^*).

Note that the final solutions (C^* and S^{**}) obtained from the first stage will be read in Step 1 and will be used to construct an initial solutions of machines sequence configuration (S^0) in Step 2. In Step 3, the initial solution (S^0) will be improved through TS procedure to generate a best solution (S^*) in terms of maximizing the CFFI.

5. Research results

5.1 An illustrative example

To illustrate the effectiveness of our developed model and algorithm, one test example is demonstrated in this section. This example consists of 10 parts, 10 machines, and 18 process routings. The maximum number of machines in each cell (U_m) is limited to 4 and the minimum number of machines in each cell (L_m) is 2. The proposed algorithm was coded in C++ using Microsoft Visual Studio 6.0 and implemented on a Intel(R) 1.66GHz PC with 1GB RAM. The computational results for each stage are described as follows.

Stage I: Cell formation and cell layout

Through the proposed HTSCF in stage I, the final solution with a total ICMD of 230 and CFFI of 10.40 % can be obtained after 0.27 seconds CPU time. The final corresponding configuration for the cell formation, cell layout, and intracellular machine layout is displayed in Figure 4.

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	1	2	2	1	2	2	1	2	1	2
1	M3		1	1	1	1					
	M7	3	3	3	3	3					
	M8	2	2	2	2	2					
2	M2	1					2	1			
	M4						1	2			
	M6						3	3			
3	M1								1	1	1
	M5				4				4	3	3
	M9								3		2
	M10								2	2	
ICMD=230, CFFI= 10.40(%)											

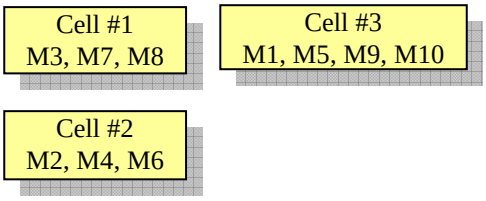


Figure 4. Final solution of stage I (cell formation, inter-cell layout)

In order to get the optimal solution, a pure integer liner model described in Section 3.1 is solved using a branch and bound (B&B) algorithm with the Lingo 8.0 software. The Lingo solver status for this example is shown in Figure 5. The optimal solution (230) is obtained in 13 seconds. In contrast, our proposed HGCFA is able to find the optimal solution in 0.27 second, thus implying the superiority of HGCFA in solution efficiency. We believe this superiority will be even more significant as problem size increases.

Figure 5. Lingo solver status of stage I

Stage II: Intracellular machine layout

Through the proposed HTSCF in stage II, the CFFI can be improved to 70.52(%) after 0.09 seconds CPU time. The final corresponding configuration for the cell formation, cell layout, and intracellular machine layout is displayed in Figure 6.

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	1	2	2	1	2	2	1	2	1	2
1	M3		1	1	1	1					
	M8	2	2	2	2	2					
	M7	3	3	3	3	3					
2	M4						1	2			
	M2	1					2	1			
	M6						3	3			
3	M1								1	1	1
	M10								2	2	
	M9								3		2
	M5				4				4	3	3
ICMD=230, CFFI= 70.52(%)											

Cell #1
M3, M8, M7

Cell #3
M1, M10, M9, M5

Cell #2
M4, M2, M6

Figure 6. Final solution of stage II (cell formation, inter-cell layout and intra-cell layout)

To evaluate the performance of our proposed HGCFA, the mathematical model described in Section 3.2 is solved using Lingo 8.0 software. The Lingo solver status is shown in Figure 7. The optimal solution (0.705202) can be obtained in less than 1 second. In contrast, our proposed HGCFA is able to find the optimal solution in 0.09 seconds, thus illustrating the superiority of HGCFA in solution efficiency. Similarly, we believe this superiority will be even more significant as problem size increases.

Figure 7. Lingo solver status of stage II

5.2 Computational results and comparisons

In order to demonstrate the effectiveness of our proposed model and methodology for cell formation and cell layout problems, four test instances (Table 4) from the literature are employed and compared the optimal solutions obtained by the branch and bound (B&B) algorithm with the LINGO 8.0 software. The computational results are summarized and compared in Tables 5 and 6. The results show that the proposed HGCFA is able to achieve global optimum for all test instances in less than 1 second. As for test instance #4 in stage I, the B&B took 121928 seconds (34 hours) to find the optimal solution (27.07). In contrast, our proposed algorithm is able to produce optimal solutions in less than 1s. These findings indicate the superiority of our proposed algorithms in solution efficiency.

Table 4. Test instances from the literature

No.	Source	Size ($m \times p \times r$)	L_m	U_m
1	Jabal Ameli *et al*. [17]	9×8×20	2	6
2	Kim *et al*.[24]	10×10×25	2	5
3	Sofianopoulou [7]	12×20×26	2	5
4	Sofianopoulou [7]	14×20×45	2	5

Table 5. Comparison of Lingo (B & B) and our HGCFA in stage I

Test instance		HGCFA		Lingo (B&B)	
No.	NC	ICMD	CPU (s)	ICMD	CPU (s)
1	2	105*	0.24	105*	5
2	2	64*	0.31	64*	18
3	3	29.83*	0.64	29.83*	271
4	3	27.07*	0.78	27.07*	121928

*: Global optimum

Table 6. Comparison of Lingo (B & B) and our HGCFA in stage II

Test instance		HGCFA		Lingo (B&B)	
No.	NC	CFFI (%)	CPU (s)	CFFI (%)	CPU (s)
1	2	61.25*	0.08	61.25*	1
2	2	77.23*	0.11	77.23*	1
3	3	27.69*	0.13	27.69*	2
4	3	30.77*	0.13	30.77*	2

*: Global optimum

6. Conclusion

CFP is the first and most difficult aspect of constructing a preliminary CMS. Considering the issues of production volume, production sequence, alternative process routings, cell layout, and the sequence of machines within cells in the design of CMS make the CFP complex but more realistic. However, very few researchers have addressed these issues simultaneously in the design of CMS. In this study, a two-stage mathematical programming model has been formulated to integrate cell formation, cell layout, and intracellular machine layout simultaneously with the considerations of alternative process routings, operation sequences, and production volume. As problems in the two stages are NP-hard, a two-stage HGCFA merging a SCM-based clustering algorithm and TS method has been proposed to solve this model quickly and effectively. Illustrative examples and comparisons have demonstrated the effectiveness of the proposed model and solution algorithm.

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