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설비능력과 작업순서를 고려한 U-라인상에서의 셀 시스템 설계

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Operation-sequence-based Approach for Designing a U-shaped Independent-Cell System with Machine Requirement Incorporated

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■ Abstract ■

This paper considers a cost model for a U-shaped manufacturing cell formation which incorporates a required number of machines and various material flows together under multi-part multi-cell environment. The model is required to satisfy both the specified operation sequence of each part and the total part demand volume, which are considered to derive material handling cost in U-shaped flow line cells. In the model several cost-incurring factors including set-up for batch change-over, processing time for operations of each part, and machine failures are also considered in association with processing load and capacity of each cell. Moreover, a heuristic for a good machine layout in each cell is newly proposed based on the material handling cost of each alternative sequence layout. These all are put together to present an efficient heuristic for the U-shaped independent-cell formation problem. Numerical problems are solved to illustrate the algorithm.

Keyword : cell formation, operation sequence, independent cell, utilization, double-combining

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1. Introduction

A manufacturing cell is a production unit for which a group of functionally dissimilar equipment are located in close proximity and dedicate to manufacturing a family of parts(products) and/or parts with similar characteristics. Such a manufacturing cell configuration is not merely an issue of rearranging the factories, but importantly an issue that involves the organizational and human behavioral aspects of manufacturing firms. The five most important reasons why the firms have been interested in establishing such manufacturing cells are related to seeking improvement in : throughput time, WIP inventory, part/product quality, response time to customer orders, and move distances/times (1997, Wemmerlov).

Based on the technical progress and managerial success of cellular manufacturing systems (CMS), the associated cellular approach has been widely considered as providing the most feasible and flexible configuration in fabrication and assembly production lines. Moreover, CMS is a feature of work organization that represents an attractive alternative to such traditional production lines as job shop and large-scale conveyor assembly line.

One of the most important problems in designing a CMS is concerned with configuring machine cells in association with part grouping. Many researches have been reported on the issue of configuring machine cells for the objective of having flexible cellular systems, in various heuristic approaches. For example, Ballakur and Steudel (1987) showed that such cell formation problems are NP-complete. Thereupon, for such problems, various heuristic approaches have been proposed based on a lot of combinatorial methods including mathematical programming, clustering approaches, graph partitioning, network flows, artificial intelligence and various methodologies. Ahmed (1991) has considered inter-cell and intra-cell moves to incorporate their associated material handling cost for making cell formation. Verma (1995) has extended the heuristic approach of Armed (1991) by adding such factors as part operation sequences and backtracking as well as demand volume. Wemmerlov (1990) has proposed a heuristic model for configuring independent cells, where an independent cell was defined as a manufacturing cell which can process all the operations required by some parts. His heuristic starts with grouping parts with similar operation sequences, and then selects their corresponding machine groups. Ho and Moodie (1993) have proposed a pattern matching heuristic procedure for a multi-product single assembly line, which is based on part operation sequences in two types of layout configurations including a line structure layout and a network structure layout

However, few integrated solution procedures have been reported in the literature to deal with the combined issue of machine requirement and economical material handling based on the operation sequences of parts. The combined issue in fact has been attracting management attention in automobile and electronic industries for their cell-type configuration (or restructuring) of manufacturing system to cope with modern market dynamics represented by multi-product small/middle-volume demands. In this regard, it may be desired to have a system composed of several independent cells where each cell can economically provide all the operations required for a group of some parts. Thereupon, it may be recommended for each independent cell to be composed of reasonable machines (not that high-speed or expensive ones, comparing with those in any large assembly/fabrication system) which are economical enough to satisfy the associated demands. This implies that the remaining issue is concerned with the questions "How many independent cells are required in the optimal sense?" and "How to build the optimal configuration of each cell?" To solve both the questions together, this paper is to consider a U-shaped system of independent cells for which a cost model is derived to represent investment on machines and material handling charge. Such a U-shaped system consideration is motivated with the characterization that it may provide shorter move distance, more reliable handling and shorter waiting in the associated cell, in comparison with large-scale conventional manufacturing lines.

In this paper, a heuristic solution procedure is developed for making cost-effective cell formations and machine layout for each cell by investigating a cost model which incorporates material handling cost and machine cost together in the proposed U-shaped independent-cell system. All the costs are described in association with such cost-incurring factors as operation sequences of parts, forward and backward handling of each part, set-up for each batch, and machine failures.

This paper is organized as follows. Section 2 introduces some notation and three basic procedures contributed to the proposed U-shaped independent-cell system. In Section 3, the solution approach and double-combining algorithm are presented. An illustrative numerical problem is solved in Section 4.

2. Procedure of Designing Cells

A new integrated procedure is to be proposed in this section under the basic assumptions given as follows :

(1) Each part operation is processed on its associated unique type of machine, where any consecutive operations performed on a machine type are treated as a combined single operation.

(2) Each independent cell is composed of various machine types each required uniquely by the associated group of parts.

(3) Material handling between machines in a U-shaped cell is performed in a rectilinear moving pattern.

(4) Each independent cell does not allow any new batch to be started until finishing the whole current batch of a part type, under the situation where work orders and material supply for part processing are determined in batch unit no matter what type of parts are processed in consecutive batch sequences.

Material handling between machines in the cell is represented by two types of moves including operation move and machine-skipping move. These two types of moves are allowed to be made along forward and backward flow direction, depending on the operation sequences of parts treated in the cell. Thus, the major cost factors considered in this paper for cell formation are outlined as :

(1) Operation move cost incurs as a part moves from one machine to adjacent machine for its next operation inside a cell. Its

(2) **Skipped move cost** incurs as some parts do not visit any machine in the cell but rather pass by it, which may require special handling.

(3) **Machine cost** incurs as a set of machine types are installed at an independent flow line cell to process all the parts allocated in the cell, while some of these machine types may be installed in duplicate among different cells.

This section presents three major sub-procedures for constructing the most economical independent cells and cell-dependent machine layouts. They include a procedure for computing material handling, a procedure for determining machine layout (sequence) for each cell, and a procedure for figuring out the processing load and overall utilization ratio of cells. These three sub-procedures are used to incorporate both material flow and machine requirement together for evaluating any change in the total system cost which may be incurred due to any feasible merging (combining) of every pair of cells to be considered for any better cell formation.

Some notation is now introduced to be used throughout this paper.

- i : Part (product) type index.
- k : Machine type index (each machine type is corresponding to each operation type).
- q_i : Average demand volume (in batch) per period for part i.
- b_i : Batch size of part i.
- h_i : Operation move cost per inter-machine move for unit of part i.
- θ_i : Skipped move cost per inter-machine skip for unit of part i.
- β_i : Backtracking multiplier.
- C_k : Machine cost per period for unit of machine type k.
- OS_i : Operation sequence of part i described in machine type.
- st_i : Set-up time for producing one batch of part i.
- t_{ik} : Net processing time for unit of part i to perform the associated operation on machine type k.
- r_k : *Up-time ratio of machine type k* [$= MTBF_k/(MTBF_k+MTTR_k)$].
  - $MTBF_k$: Mean time between failures of machine type k.
  - $MTTR_k$: Mean time to repair a machine type k.
- APT : Expected available production time of cell per period (i.e., given as working hours per week or per month, etc.).
- NO_i : Number of operations of part i. (i.e., number of inter-machine moves for operation in a given cell for part i).
- NS_i : Number of machine skipping moves in a given cell for part i.
- NB_i : Number of inter-machine backward moves in a given cell for part i
- NC : Number of cells in the overall system.
- NP : Number of part types in the overall system.
- U_e : Utilization ratio of cell e, defined as a ratio of the total loading time for processing all parts allocated to cell e to the net available time of cell.
- MC_e : Total machine cost for serving all the parts in cell e.
- MH_e : Total material handling cost for moving parts between machines in cell e.

TC_e : Total system cost in cell e ($TC_e = MC_e + MH_e$).

P_e : Set of parts served in cell e.

M_e : Set of machine types in cell e.

2.1 Computation of material handling cost inside each cell

It is noted that the number of total moves of each part is represented by the sum of the number of total inter-machine moves for part operations and the number of total machine-skipping moves in a given cell. Each backward move (backtracking) often causes more complicate material handling than its forward move, so that some penalty should be additionally charged for such backward flow. Therefore, in each U-shaped cell with rectilinear moving pattern considered, the total material handling cost of unit part based on its operation sequences, denoted by H_i, can be defined as by incorporating all the operation moves, the machine-skipping moves, and backward flow

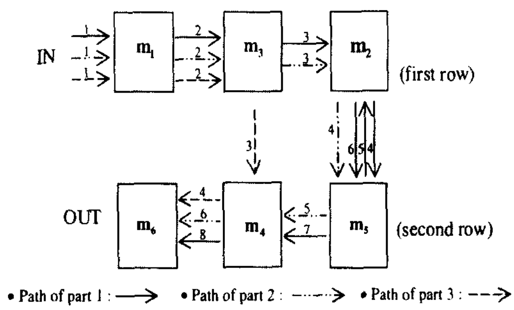
$$H_i = NO_i \cdot h_i + NS_i \cdot \theta_i + NB_i \cdot \beta_i \cdot h_i \quad (1)$$

Moreover, NS_i and NB_i can be counted from the operation sequences of each part i allocated in the cell. Thus, the total material handling cost per period of all the parts treated in any given cell e, MH_e, can be easily computed based on Eq.(1) as

$$MH_e = \sum_{i \in P_e} (H_i \cdot b_i \cdot q_i) \quad (2)$$

Eqs.(1) and (2) will be used for computing the material handling cost of each part in the cell throughout this paper.

For instance, consider a situation where the machine layout in a cell is given as ML=[1-3-2-5-4-6] and the operation sequences of any three parts to be treated in the cell are specified as $OS_1 = \{1, 3, 5, 2, 4\}$, $OS_2 = \{1, 3, 2, 5, 4\}$ and $OS_3 = \{1, 3, 4, 6\}$, respectively. Then, from the moving path of each part as shown in [Figure 1], NS_i, NB_i and H_i can be figured out as in <Table 1>. The number on each path in [Figure 1] represents the flow sequence number (FSN) of moves between machines for each part.



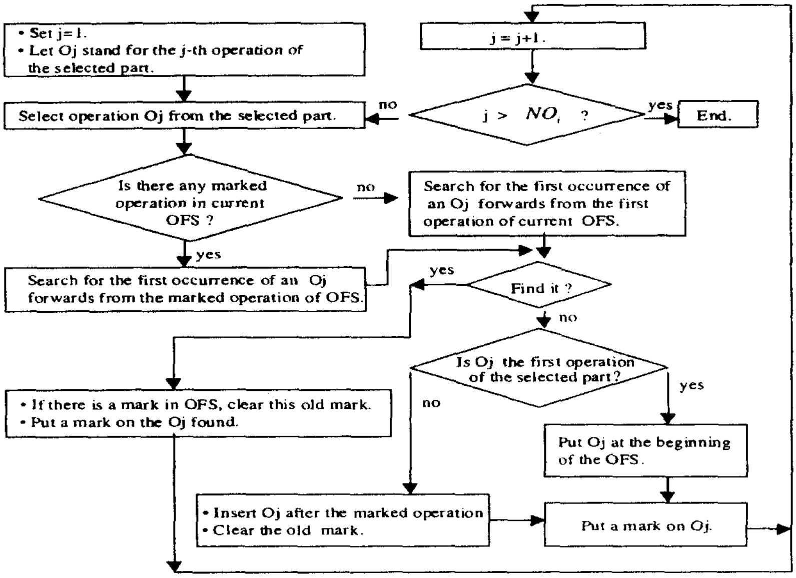
[Figure 1] The rectilinear flow path of three parts in a U-shaped cell

2.2 Determination of machine layout inside each cell

The machine sequence in each cell should be

<Table 1> Material handling cost per unit part for two moving methods

Part i	Move for operation		Machine-skipping move		Backward move		H_i
	FSN	NO_i	FSN	NS_i	FSN	NB_i	
Part 1	{1, 2, 4, 5, 7}	5	{3, 6, 8}	3	{5}	1	$(5+\beta_i) \cdot h_1 + 3\theta_1$
Part 2	{1, 2, 3, 4, 5}	5	{6}	1	-	0	$5h_2 + \theta_2$
Part 3	{1, 2, 3, 4}	4	-	0	-	0	$4h_3$



[Figure 2] The modification procedure of operation flow sequence (OFS)

determined such that any backward move of each part occur as little as possible so as to minimize the material handling cost. For this purpose, a heuristic method is proposed to derive the machine layout based on the operation sequences of all the parts treated in a given cell. Its detailed steps are described as follows :

(1) Select the part with the largest number of operations from among all the parts treated in the cell. If there is any tie, select the part with the larger demand volume. If there is any tie again in demand volume, the tie can be broken at random. Then, use the sequence of this part as an operation flow sequence (OFS).

(2) Delete the selected part out of the set of the remaining parts in the cell.

(3) From among the remaining parts, select another part with the largest number of operations, and update the current OFS by incorporating any different operation sequence which is newly required by the selected part as shown in the flow chart of [Figure 2], referring to Ho(1993).

(4) Repeat (2)-(3) until all the remaining parts in the cell are considered to make such OFS modification.

(5) From the resulting OFS, construct all possible machine sequence alternatives each being composed of a set of its associated unique machine types. Note that each machine sequence is corresponding to each operation sequence.

(6) For each of the machine sequence alternatives, count the number of machine-skipping moves and the number of backward moves, and then compute the associated material handling cost, according to the operation sequences of all parts to be treated in the cell.

(7) Determine the machine layout that gives the minimum material handling cost, from among

all the possible alternatives.

Consider an example for determining the machine layout that has problem data as shown in <Table 2>. The proposed algorithm finds one sequence of [1-3-2-5-4-6] which is more cost-effective than another sequence of [1-3-5-2-4-6] in material handling cost, among two possible alternatives, as shown in <Table 3>.

〈Table 2〉 The problem data for 5 machines and 2 parts cell

Part i	Operation Sequence (OS_i)	h_i	θ_i	β_i	b_i	q_i
1	(1, 3, 5, 2, 4)	0.2	0.1	2	20	10
2	(1, 3, 2, 5, 4)	0.4	0.2	2	50	10
3	(1, 3, 4, 6)	0.2	0.1	2	30	10

〈Table 3〉 Material handling cost for each alternative sequence

Alternative sequence	Layout configuration	Part i	h_i	MH_e
1-3-2-5 -4-6	1 - 3 - 2	1	$(5+\beta_i)\cdot h_1+3\theta_1$	1640
	|	2	$5h_2+\theta_2$	
	6 - 4 - 5	3	$4h_3$	
1-3-5-2 -4-6	1 - 3 - 5	1	$5h_1+\theta_1$	1960
	|	2	$(5+\beta_2)\cdot h_2+3\theta_2$	
	6 - 4 - 2	3	$4h_3$	

2.3 Processing load and utilization ratio of cell

Cell operation effectiveness (productivity) may decrease subject to two significant factors including set-up and machine failure. This provides us with the motivation of proposing a procedure for determining an appropriate utilization ratio of each cell to satisfy any given demand volume subject to any functional constraints associated with the two factors.

There always exists capacity unbalance among machines in each cell, because the net processing time (t_{ik}) varies with part i and machine k. In the case of consecutive flow production, the processing time of one batch of part i is dependent on the machine which has the maximum processing time of the part, denoted by $t_i^{\max}$, that is $t_i^{\max} = \max_{k\in\Omega_i}\{t_{ik}\}$, where Ω_i represents the set of machine types for part i to visit for its operations.

In order to process one batch of part i, a set-up is needed to prepare for the batch change-over during the time of st_i. After that, the first unit of part i can come into the cell and exit from the cell after the time amount of ($\sum_{k\in\Omega_i} t_{ik} + NO_i + NS_i)\cdot t_0$) is elapsed, where t_0 represents the inter-machine move time between adjacent machines. Since all the ($b_i - 1$), remaining units of part i can follow one by one with the time interval of $t_i^{\max}$, the net processing time of one batch of part i becomes ($\sum_{k\in\Omega_i} t_{ik} + (NO_i + NS_i)\cdot t_0) + (b_i - 1)\cdot t_i^{\max}$. Thus, the processing time load per period of part i in a given cell, T_i, can be expressed as

$$T_i = [\, st_i + (\sum_{k\in\Omega_i} t_{ik} + (NO_i + NS_i)\cdot t_0) + (b_i - 1)\cdot t_i^{\max}\,]\cdot q_i \quad (3)$$

Note that both the values of NS_i and T_i change according to the machine layout of the cell where part i is processed, while NO_i is constant for part i. Thus, the utilization ratio of a given cell e, a ratio of the total processing time load to the net available production time, can be expressed as $U_e = (\sum_{i\in P_e} T_i)/\{APT\cdot \prod_{k\in M_e} r_k\}$, since the total processing time load for all parts of the cell is represented by the sum of every T_i derived by Eq. (3) and the up-time ratio of the cell is derived as $\{APT \cdot \prod_{k \in M_c} r_k\}$ due to independent machine failures and repairs.

3. Solution approach and algorithm

The heuristic procedure is now derived in this section, which is composed of two major steps including initial cell formation step and cell improvement step. In the first step, the procedure of the initial cell formation constructs each cell to be composed of machines corresponding to a single part, and then computes all the associated cost including material handling cost, machine cost and total system cost for each cell. That is, each initial cell is treated as dedicated to a single part. Then, each initial cell is to be treated for its improvement in the second step where each pair of the initial cells are evaluated for any feasibility of their merging (combining) together into a larger cell.

3.1 Cell combining in each iteration

As combining two separate cells v and w into a combined larger cell (v,w), the material handling cost of the combined cell increases, while the machine cost decreases, in comparison with the sum of the individual costs of the two cells. Let S be a set of machine types, which are included commonly in two separate cells v and w. The machine cost saving due to their combining into a larger cell (v,w), denoted by MCS_{vw}, can be expressed as

$$MCS_{vw} = MC_v + MC_w - MC_{vw} = \sum_{k \in S} C_k \quad (4)$$

This implies that the total system cost may fluctuate (increase or decrease), depending on each pair of cells, when combining two cells together. Therefore, the solution search in this paper is made for a cost-effective cell design in an iterative cell-combining process such that any contribution of cost saving in total system cost can be ensured under the restriction of cell utilization requirement.

The processing time load of part i (T_i) in the combined cell (v, w) can be derived easily when any two separate cells v and w are combined. In each initial cell v or w, there does not exist any machine-skip move since each initial cell is composed of only the machine types required uniquely by part i. That is, only inter-machine moves appear in each initial cell. Thus, the processing time load of part i in an initial cell, T_i^0, can be represented as follows from Eq. (3)

$$T_i^0 = [\, st_i + (\sum_{k \in \Omega_i} t_{ik} + NO_i \cdot t_0) + (b_i - 1) \cdot t_i^{\max} \,] \cdot q_i \quad (5)$$

Then, the processing time load of part i (T_i) in the combined cell (v, w) becomes

$$T_i = T_i^0 + NS_i \cdot t_0 \cdot q_i \quad (6)$$

That is, T_i can be obtained easily by summation of $NS_i \cdot t_0 \cdot q_i$ and T_i^0 in the initial cell. Eq. (6) can reduce a lot of computation time in recomputing the processing time load (T_i) at each iteration. Moreover, the utilization ratio of the combined cell (v, w) can be expressed as

$$U_{vw} = \frac{\sum_{i \in P_v} T_i + \sum_{i \in P_w} T_i}{APT \cdot \prod_{k \in M_{vw}} r_k} \quad (7)$$

since the total processing time load of parts in the combined cell is represented by the sum of the processing time loads of every part in the separate cells. Note that in case of $U_{vw} > 1$, the combined cell (v, w) should not be considered as a solution candidate, since the processing time load of the combined cell exceeds its capacity.

3.2 Branching in each iteration

After the cost saving computation is completed for each pair of cells, the cell formation improvement is tried by two methods including single-combining and double-combining methods. The single-combining method is considered to create one branched problem (improved cell formation) at each iteration by combining a pair of two cells together which can give the greatest cost savings (CS^1) among all the pairs of cells. The double-combining method is also considered to create two branched problems from any current cell formation at each iteration. The first branched problem is created by combining another pair cells which can give the greatest cost saving (CS^1) and the second branched problem is created by combining a pair of next greatest cost saving (CS^2). That is, if any of CS^1 and CS^2 values is positive for each branched problem at the current iteration, then the algorithm moves to the next iteration for any further cost saving branching. Otherwise, it stops any further branching from the current branched problem. If no new problem is branched from the current iteration, then a final solution is obtained, which gives the maximum of total system cost saving, from among all branched problems examined.

The proposed double-combining method certainly provides a better solution than any single-combining approach of combining together each pair of cells having only the greatest cost saving (CS^1), since it can search for a feasible solution among the more enlarged solution space. Note that the solution procedure of double-combining method comprises that of single-combining method.

3.3 Solution Algorithm by double-combining method

STEP 1 : Initial cell formation

(1-1) $NC = NP$ (initially each cell is considered to serve a single part).

(1-2) For each initial cell v composed of the machine types corresponding to a part, compute $MC_v = \sum_{k \in M_v} C_k$, $MH_v = NO_i \cdot h_i \cdot b_i \cdot q_i$ and $TC_v = MC_v + MH_v$.

(1-3) Compute the processing time load (T_i^0) of each part in the initial cell.

STEP 2 : Cell formation improvement

(2-1) *Iteration* = 1.

(2-2) Let $v = 1$.

(2-3) Let $w = v + 1$.

(2-4) For a candidate pair of cells v and w to be combined together, determine the machine layout based on the material handling cost of all the associated machine sequence alternatives, by the heuristic method presented in Section 2.2.

(2-5) Compute the processing time load of part i by Eq. (6), that is, $T_i = T_i^0 + NS_i \cdot t_0 \cdot q_i$.

(2-6) Compute the utilization ratio (U_{vw}) of the combined cell from Eq. (7) in Section 3.1. If $U_{vw} > 1$, then go to Step(2-9). If $U_{vw} \le 1$ then compute the machine cost saving(MCS_{vw}) from Eq. (4) in Section 3.1.

(2-7) Compute the material handling cost saving (MHS_{vw}) in the combined cell by using the associated material handling cost (MH_{vw}) computed in Step(2-4), that is, $MHS_{vw} = MH_v + MH_w - MH_{vw}$. Note that MHS_{vw} is a non- positive value.

(2-8) Compute the associated total cost saving in the combined cell, that is, $CS_{vw} = MCS_{vw} + MHS_{vw}$.

(2-9) $w = w + 1$; if $w > NC$, then go to Step (2-10), else go back to Step(2-4).

(2-10) $v = v + 1$; if $v = NC$, then go to Step (2-11), else go back to Step(2-3).

(2-11) Find the pair of cells x_1 and y_1 which is associated with the greatest cost saving $CS^1_{x_1y_1}$and find the pair of cells x_1 and y_1 which is associated with the next greatest $CS^2_{x_2y_2}$ among all the cost saving values of possible pairs. If $CS^1_{x_1y_1} \le 0$ or $U_{vw} > 1$ for all pairs of v and w, then go to Step(2-14), else go to Step (2-12).

(2-12) Create the new branched problem by combining the associated two cells x_1 and y_1 together, and update the associated part set and machine set of the combined cells, respectively, i.e., $P_{x_1} = P_{x_1} \cup P_{y_1}$, $M_{x_1} = M_{x_1} \cup M_{y_1}$.

(2-13) If $CS^2_{x_2y_2} \le 0$, then go to Step(2-14), else create another new branched problem by combining the associated two cells x_2 and y_2 together, and update the associated part set and machine set of the combined cells, respectively, i.e., $P_{x_2} = P_{x_2} \cup P_{y_2}$, $M_{x_2} = M_{x_2} \cup M_{y_2}$.

(2-14) If all branched problems are solved at the current iteration, then go to Step(2-15), else select another branched problem at the current iteration and go back to Step(2-2).

(2-15) If no new problem is branched from the current iteration, then stop any further branching and go to Step(2-16), else,

(1) decrease the number of cells, that is, $NC = NC - 1$,

(2) update the cell index in the sequential order, that is $v=1,2,\cdots,NC$, for each new problem branched from the current iteration,

(3) *iteration*=*iteration*+1,

(4) select a new branched problem and go back to Step(2-2) to start the next iteration.

(2-16) Obtain the final solution as the cell formation, giving the maximum of total system cost saving from among all branched problems examined until now.

This algorithm does certainly search for a good solution within finite searching steps, because it groups two cells (contributing the greatest cost saving or the next greatest one) into a larger cell at a time in the cell improvement step of the proposed algorithm. Moreover, its effectiveness is prominent mainly due to the cell formation characteristics favoring any combining of two cells with the similar operations of parts so as to reduce the total system cost.

〈Table 4〉 Problem data for the problem of 7 parts and 5 machines

Part i	OS_i	h_i	θ_i	b_i	q_i	T_i^0
1	(1, 2, 3, 4, 5)	1.0	0.5	200	10	8000
2	(1, 2, 4, 5)	0.8	0.4	100	10	5000
3	(3, 4, 5)	0.4	0.2	300	10	6000
4	(2, 3, 4, 5)	0.6	0.3	200	10	4000
5	(2, 1, 4, 5)	0.2	0.1	300	10	4000
6	(1, 2, 5)	0.1	0.05	150	10	3000
7	(2, 3, 5)	0.4	0.2	150	10	8000
r_k	(.99, .99, .99, .99, .99)	APT = 15000 minutes/month				
C_k (\$/month)	(100, 50, 50, 100, 100)					

4. Numerical Examples

A numerical examp le is solved to illustrate how the proposed heuristic algorithm works to find a good design of U-shaped independent cells. Five machines and seven parts are considered for the problem with backtracking multiplier $\beta_i = 1$ for all parts, and inter-machine moving time t_0=1 as listed in <Table 4>.

In the beginning, each initial cell is formed in association with a single part. Then, the material handling cost of the initial cells are computed as MH = (800, 240, 240, 360, 180, 40, 120) by incorporating forward/backward move, and the machine cost of the cell as MC = (400, 350, 250, 300, 350, 250, 200, 800). Then, the total system cost of the initial cell is computed as TC = (1200, 590, 490, 660, 530, 290, 320), which is obtained as the sum of MH and MC.

Starting with 7 separate the combining procedure for improving such initial cells is implemented with each candidate of all possible pairs to obtain their corresponding cost savings in total system cost, CS_{vw}. For instance, a combined pair (1,2) of cell 1 and cell 2 has a unique machine layout sequence, ML_{12} = [1-2-3-4-5]. Moreover, the processing time load of part 1 is computed as $T_1 = T_1^0$ = 8000 and the processing time load of part 2 computed as $T_2 = T_2^0 + NS_2 \cdot t_0 \cdot q_2$ = 5000 + (1)(1)(10) = 5010, where one machine-skip occurs in the combined cell. Then, the utilization ratio of the cell (1,2) is computed as U_{12} = (8000 + 5010) / (15000 0.9501) = 0.913 (<1). MH_{12}= (4)(1)(10)(20) + (4)(1)(8)(10) = 1120, and also MHS_{12} and MCS_{12} are also computed as $MHS_{12} = MH_1 + MH_2 - MH_{12}$ = 800 + 240 - 1080 = -40 and MCS_{12} = 100 + 50 + 100 + 100 = 350. Consequently, the cost saving of combined cell (1,2) is, CS_{12} = 310. Similarly, such cost savings by all other possible pairs are computed as shown in <Table 5>.

〈Table 5〉 The 66 cost saving matrix for all possible pairs of cells at the iteration 1

Cell v \ Cell w	Part set	2	3	4	5	6	7
		{2}	{3}	{4}	{5}	{6}	{7}
1	{1}	**310**	130	**240**	150	220	140
2	{2}		40	150	230	240	50
3	{3}		-	190	50	20	60
4	{4}			-	160	70	170
5	{5}				-	200	60
6	{6}					-	110

It is seen from <Table 5> that the greatest cost saving value, CS_{12}^1 = 310, is selected to combine the associated two cells 1 and 2 together, and the next greatest value, CS_{14}^2 = 240, is selected to combine the associated two cells 1 and 4 together, respectively. That is, the initial cell is branched into two problems of six cells, branched problem 1 (BP1) and branched problem 2 (BP2).

<Table 6> The 5×5 cost saving matrix for all possible pairs of cells at the iteration 2 for BP1

Cell v \ Cell w	Part set	2 {3}	3 {4}	4 {5}	5 {6}	6 {7}
1	{1, 2}	×	×	×	×	×
2	{3}	-	**190**	50	20	60
3	{4}		-	160	70	170
4	{5}			-	**200**	60
5	{6}				-	110

At the second iteration to improve the branched problem 1 as shown in <Table 6>, the greatest cost saving, CS^1_{45} = 200, is selected to combine the associated cell 4 and cell 5 together, and the next greatest, CS^2_{23} = 190, is selected to combine the associated two cells 2 and 3 together, respectively. Note that all CS_{vw} values in <Table 6> can be obtained from those in <Table 5>, since only CS_{vw} values associated with cell 1 combined at the just preceding iteration need to be recomputed when constructing the new cost saving table. The marks "×" in <Table 6> represent the situation of $U_{vw} > 1$.

<Table 7> The 55 cost saving matrix for all possible pairs of cells at the iteration 2 for BP2

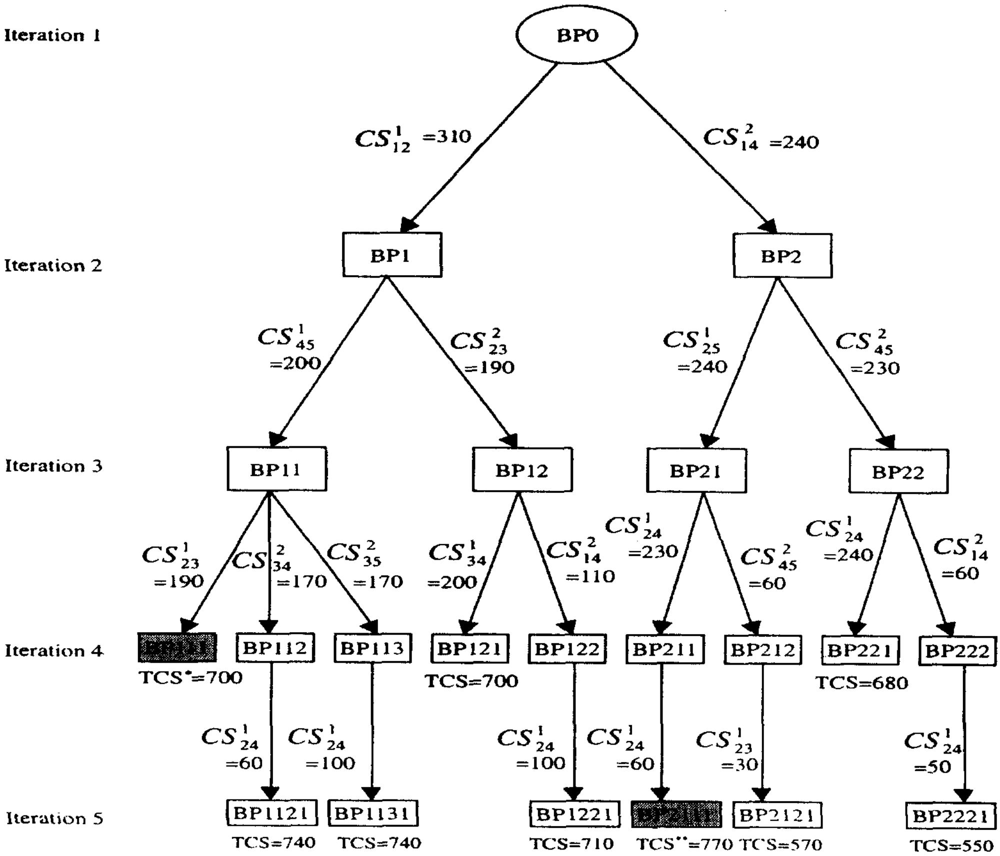
Cell v \ Cell w	Part set	2 {2}	3 {3}	4 {5}	5 {6}	6 {7}
1	{1,4}	×	×	×	×	140
2	{2}	-	40	**230**	**240**	50
3	{3}		-	50	20	60
4	{5}			-	200	60
5	{6}					110

At the second iteration of improvement for the branched problem 2 as shown in <Table 7>, the greatest cost saving value, CS^1_{25} = 240, is selected to combine the associated cell 2 and cell 5 together, and the next greatest value, CS^2_{24} = 230, is selected to combine the associated two cells 2 and 4 together, respectively.

Continuing the iterative procedure in the way of the proposed double-combining method, the solution diagram can be drawn as depicted in [Figure 3].

The final solution by the proposed double-combining approach provides 3 cells that are individually associated with part sets {1, 4}, {2, 5, 6} and {3, 7}. The corresponding machine layout to each of the 3 cells is configured, based on the proposed heuristic in Section 2.2 such as [1-2-3-4-5] in cell 1, [1-2-3-4] in cell 2, and [2-3-4-5] in cell 3, respectively. A solution by a single-combining approach can also provide 4 cells that are individually associated with part sets {1, 2}, {3, 4}, {5, 6} and {7}. The corresponding machine layout to each of the 4 cells is configured such as [1-2-3-4-5] in cell 1, [2-3-4-5] in cell 2, [2-1-4-5] in cell 3 and [2-3-5] in cell 4, respectively. This shows that the proposed double-combining approach certainly provides a better solution than the single-combining approach as shown by their respective values of TCS^* = 700 and TCS^{**} = 770 in [Figure 3].

The proposed algorithm is now evaluated with five different numerical problems for its effectiveness by comparing the total system cost of the final solutions of the single-combining approach with that of the double-combining approach. The effectiveness is measured in percentage as a ratio of the total system cost of the final solution determined by the single-combining approach to that of the double-combining



$CS^1_{x_1y_1}$: Greatest cost saving in each branched problem.
$CS^2_{x_2y_2}$: Next greatest cost saving in each branched problem.
TCS : Total cost saving that is cumulative from the initial cell at each final branching point.
TCS*, TCS** : Total cost saving of final solution of single-combining method and double-combining method, respectively.

[Figure 3] Solution search diagram by the double-combining approach

approach. The resulting effectiveness measures are listed as shown in <Table 8>, where the mean system cost for each problem is computed by averaging the total system costs of ten solutions which are all found by use of the cost values(h_i, C_k) generated by random number generators. The results in <Table 8> show that the double-combining approach provides more cost-effective solutions within the range of 0.25~3.32% than the single-combining approach in total system cost.

〈Table 8〉 Effectiveness of the proposed heuristic algorithm measured in terms of total system cost

Problem type (parts × machines)	Total system cost of heuristic algorithm		Effectiveness (%) of Double-combining method
	Single-combining method	Double-combining method	
3 × 5	1421.1	1417.5	99.75%
5 × 7	4072.2	4031.1	98.99%
7 × 5	4874.4	4800.3	98.48%
9 × 12	59498.5	57862.3	97.25%
12 × 9	67895.3	65641.2	96.68%

5. Summary and Conclusion

This paper presents an efficient heuristic procedure of designing an independent flow line cell system in an iterative process of pairwise cell combining. In deriving the procedure, several combining properties for cell formation are characterized. The resulting major features of the procedure are summarized as follows :

- Being an integrated cell formation procedure for a multi-part multi-cell, focused on the number of machines (to be employed) and material flow,
- Computing the explicit moving behavior of parts in a U-shaped flow line cell,
- Finding a good machine layout for each cell in the heuristic approach of utilizing material handling cost based on the associated part operation sequences,
- Presenting an explicit computation of cell utilization ratio,
- Being sensitive to part demand volume, material handling cost per move, machine cost, and capacity unbalance between machines,
- Being easily extended to the situations of incorporating some additional restrictions including capital investment, number of cells, and maximum cell utilization.

A further study may immediately be made on flexible manufacturing systems where inter-cell move or multiple operations on a machine are permitted.

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