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AN ELECTROMAGNETISM-LIKE MECHANISM METHOD FOR SOLVING DYNAMIC CELL FORMATION PROBLEMS

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ABSTRACT

This study develops a durable cell formation model for simultaneous multi-period manufacturing situations. The model combines group efficacy and efficacy variance for the purpose of maximizing group efficacy for each period, as well as minimizing efficacy variance in all periods. Due to the fact that dynamic cell Formation is a NP-hard problem, this study uses an electromagnetism-like mechanism to solve the problem. The results show that while the proposed method may not achieve the maximum efficacy for each period, it can obtain better objective function value in multi-period circumstances and maintain a good variation balance in all periods.

Keywords: Cellular manufacturing system, Dynamic cell formation, Electromagnetism-like mechanism.

1. INTRODUCTION

Due to recent changes in the competitive manufacturing environment, such as lower inventory volumes, increased variety, etc., companies have acknowledged a need to select a more suitable manufacturing process structure in order to satisfy customer requirements. With this in mind, cellular manufacturing is seen as far more suitable than other systems. Cellular manufacturing systems combine the advantages of job-shop manufacturing and flow manufacturing. When designing a cellular manufacturing system, the most important steps are part families and machine cells, called cell formation (Wemmerlov and Hyer, 1987). Over time, the manufacturing situation is likely to change in different periods, such as processed part types, part quantities, part lot sizes, etc.

Because the manufacturing situations in different periods are likely to change, the existing cell formation may not be appropriate for the next period. This study therefore explores the multi-period factor in its cell formation design. Few studies have been conducted on dynamic cell formation, though some proposed methods used for dynamic cell formation include mathematical programming, genetic algorithm, and hybrid algorithm. This study proposes an electromagnetism-like mechanism (EM) for solving the cell formation problem in a multi-period environment.

2. LITERATURE REVIEW

According to previous researches on cellular manufacturing systems, this kind of system can reduce the cost of handling parts and material, shorten production lead time and production flow time, and reduce required in-process inventory quantities. Other benefits include reduced inter-cell and intra-cell movements, shortened machine set-up times, reduced exceptional elements, reduced machine bottle-neck costs, reduced overall costs, reduced machines idle times, reduced numbers of duplicate machines, reduced inventory costs, reduced machine relocation costs, increased machine utilization and increased productivity and consistency (Defersha and Chen, 2008). Torkul *et al.* (2006) used fuzzy logic to design part families and machine cells, and compared the design difference between fuzzy and non-fuzzy clustering algorithms. Their results showed that a fuzzy clustering algorithm yielded a better solution. Kor *et al.* (2009) used a genetic algorithm to develop a cellular manufacturing system, and aimed to minimize both the movement between cells and cell load changes. Four drawbacks may occur with such a cellular manufacturing system (Sharma, 2007). They are: (1) Increased capital investment, (2) Lower utilization of machinery and equipment, (3) Labor restrictions and (4) Poor productivity in the dynamic environment. In order to overcome some of these drawbacks, this study considers a multi-period environment in its cell formation design.

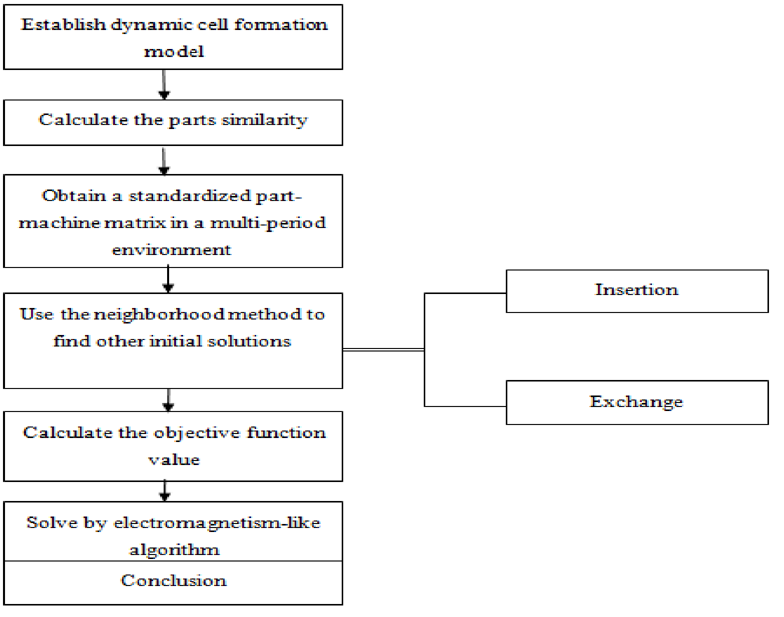
There are very few studies that consider a multi-period environment or stochastic demand in their cell design. Generally, this kind of problem is called dynamic cell formation (DCF). In a dynamic environment, manufacturers may need to manufacture different parts in each period, or there may be new kinds of parts to produce in the next period. Therefore, the designed cell formation may not be appropriate for future manufacturing situations (Papaioannou and Wilson, 2009). The dynamic cellular manufacturing system (DCMS) proposed by Rheault *et al.* (1995) mainly discussed the change over time of machines and parts in the cells. This situation may need to reconsider the cost, facility layout, machine utilization and so on. Tavakkoli-Moghaddam *et al.* (2007) proposed a new non-linear mathematical programming for a dynamic cellular manufacturing system. They minimized not only inter-cell and intra-cell costs, but also considered the cell layout under stochastic demand. Safaei *et al.* (2008a) used hybrid simulated annealing to solve an extended model of a dynamic cellular manufacturing system. They minimized the fixed cost and the variable cost of machine, inter-cell and intra-cell movements, as well as relocation costs. Defersha and Chen (2006) proposed a dynamic cell formation model to minimize the purchasing cost of machines, machine maintenance costs, the handling cost of products and parts, machine and tool operation costs, production and assembly costs and the cost of subcontracting. Wang *et al.* (2008) established a non-linear multi-objective for dynamic cell formation. They minimized machine relocation costs, and the variation of machine utilization. Finally, they used CPLEX to solve a case involving three periods. Safaei *et al.* (2008b) used a fuzzy programming approach for a cell formation problem with dynamic and uncertain conditions. The final results showed that this method could obtain the optimal solution for small test problems, but required significant computation time for large-scale problems. Deljoo *et al.* (2010) established a dynamic cell formation model. They considered the purchase and amortization costs of machines in each period, the operation costs, the cost of inter-cell movements and the cost of machine relocation in each period. Finally, they compared the solving efficiency with that of genetic algorithm. The results showed that the genetic algorithm was more efficient, and could obtain the optimum solution with less computation time.

An electromagnetism-like mechanism algorithm was proposed by Bïrbïl and Fang (2003). This algorithm is a method for solving optimization problems. The algorithm can be divided into four steps: initialization, local search, calculation of total force vector, and movement according to the total force. Some papers on electromagnetism-like mechanism algorithms for solving optimization problems include Tsou and Kao (2006), who used an electromagnetism-like mechanism algorithm to solve multi-objective optimization problems. They compared the results of their proposed method with those of a strength Pareto evolutionary algorithm. The results showed that the strength Pareto evolutionary algorithm was more efficient than the electromagnetism-like mechanism algorithm in solving small-scale problems, but that the efficiency of the two methods for large-scale problems was similar. Chang *et al.* (2009) used a hybrid electromagnetism-like algorithm for a single machine scheduling problem. Their results showed that this hybrid algorithm was more efficient than genetic algorithm. In this paper, a new EM-based approach is proposed to solve dynamic cell formation problems.

3. THE PROPOSED METHOD

The proposed method first calculates the similarity between every pair of parts in multiple periods based on group technology. Group technology uses the similarity of parts and groups required by machines to form a cell. By calculating the similarity of parts, a standardized part-machine matrix in multi-period environment can be obtained. This standardized part-machine matrix can then be used to compute the value of the objective function. Finally, an electromagnetism-like algorithm is used to solve the dynamic cell formation problem. The design steps of dynamic cell formation are shown in Figure 1.

Fig-1. The proposed method



3.1. The Dynamic Cell Formation Model

The dynamic cell formation model is based on group efficacy (Kumar and Chandrasekharan, 1990), and aims to maximize the group efficacy for each period and minimize the variation of the group efficacy. The notations are as follows:

g: Cell index (g=1, …, G)

k: Machine type index (k=1, …, K)

j: Part type index (j=1, …, J)

p: Time period index (p=1, …, P)

CV: The index of variation of the group efficacy under the multi-period environment

The objective function is as follows:

$$Max \quad \sum_{p=1}^{P} \frac{1-\varphi_p}{1+\emptyset_p} - CV \tag{1a}$$

The objective is subject to constraints as follows:

$$\sum_{k=1}^{K} V_{kgp} = 1 \quad \forall k,p \tag{1b}$$

$$\sum_{j=1}^{J} U_{jgp} = 1 \quad \forall j,p \tag{1C}$$

$$U_{jgp},\ V_{kgp} \in \{0,1\} \tag{1d}$$

$$CV = \frac{\sqrt{\sum_{p=1}^{P}\left(\frac{1-\varphi_p}{1\div\emptyset_p} - \sum_{p=1}^{P}\frac{1-\varphi_p}{1\div\emptyset_p}\div P\right)^2}}{\sum_{p=1}^{P}\frac{1-\varphi_p}{1\div\emptyset_p}\div P} \tag{1e}$$

Equation (1a) is the objective function representing the summation of the group efficacy in each period subtracted from the variation of the group efficacy under the multiple periods. Equation (1b) ensures that each machine is only assigned to one cell in each period. Equation (1c) ensures that each part is only assigned to one cell in each period. Equation (1d) represents Ujgp and Vkgp, which are 0-1 integers. Equation (1e) is the calculation method of CV.

3.2. Obtain the Standardized Cell Formation under the Multi-Period Environment

Assume that there are two different manufacturing requirements in two periods, and there are five and six different kinds of parts to be manufactured in the first and second periods, respectively. There are a total of five types of machines in these two periods. Figures 2 and 3 illustrate the part-machine matrix in the first and second periods, respectively. According to Figures 2 and 3, there is a new part (Part 6) to be manufactured in the second period.

Figure-2. Part-machine matrix in the first period

	P1	P2	P3	P4	P5
M1	0	0	1	0	1
M2	0	1	1	0	0
M3	1	0	1	1	0
M4	0	1	1	0	1
M5	1	0	0	1	0

Figur-3. Part-machine matrix in the second period

	P1	P2	P3	P4	P5	P6
M1	0	0	1	0	1	0
M2	0	1	1	0	0	0
M3	1	0	1	1	0	0
M4	0	1	1	0	1	1
M5	1	0	0	1	0	1

First, the similarity coefficient between pairs of parts is calculated (Cheng *et al.*, 2001). The formula of the similarity coefficient is as follows:

$$S_{ij}=\frac{C_{ij}}{T_i+T_j-C_{ij}} \qquad \ldots\ldots(2)$$

S_{ij} represents the similarity between part-i and part-j. C_{ij} represents the number of machines that manufacture part-i and part-j at the same time. Taking part-1 and part-3 as an example, part-1 is manufactured by machine-3 and machine-5, and part-3 is manufactured by machine-1, machine-2, machine-3 and machine-4. The similarity coefficient $S_{13}=\frac{1}{2+4-1}=0.2$. The other similarity coefficient can be computed in the same way. Table 1 shows the similarity coefficient between parts.

Table-1. The similarity coefficient between parts

	P1	P2	P3	P4	P5	P6
P1		0	0..2	1	0	0.33
P2			0.5	0	0.33	0.33
P3				0.2	0.5	0.2
P4					0	0.33
P5						0.33
P6						

According to the similarity coefficient, part families are grouped based on the value. The assignment rule of machines to cells is made according to the need for the machines to manufacture the parts. As shown in Table 1, the maximum similarity coefficient is S14. Part-1 and part-4 are then grouped into a part family. Part-1 and part-4 are manufactured by machine-3 and machine-5, so machine-3 and machine-5 are grouped into a machine cell. The other part family and machine groups follow in the same way. Figure 4 shows the standardized part-machine diagonal matrix, referring to designed situation as T1.

Figure-4. Standardized part-machine diagonal matrix (T1)

	P1	**P4**	**P6**	**P3**	**P2**	**P5**
M3	1	1	0	1	0	0
M5	1	1	1	0	0	0
M1	0	0	0	1	0	1
M4	0	0	1	1	1	1
M2	0	0	0	1	1	0

3.3. Use the Neighborhood Method to Find other Initial Solutions

Insertion and Exchange are further applied as local search steps, as proposed by Belarmino *et al.* (2001), in order to generate other initial solutions. To avoid a poor combination of groups, and to enhance the efficiency of the local search, any attempt to move parts must meet the following rules:

1. If Sij=1, Pi and Pj may not move. In Table 1, the similarity coefficient between part-1 and part-4 is 1, so part-1 and part-4 cannot move.
2. If Pi is randomly selected from Cell X for insertion into Cell Y, then Pi has to have similarity with the other parts in Cell Y.

3. If Pi is selected from Cell X to replace P_j in Cell Y, the similarity coefficient of P_i with the other parts in Cell Y may not be zero, and P_j with the other parts in Cell X may not be zero. P_i and P_j must have used the same machines in Cell Y and the machines in Cell X.

Insertion is a movement method that randomly selects a part from a cell, and then inserts that part to other cells. Two cell formations can be obtained through Insertion, as shown in Figures 5 and 6. These two designed results are called T_2 and T_3.

Figure-5. Part-machine matrix through Insertion (T_2)

	P1	P4	P6	P3	P2	P5
M3	1	1	0	1	0	0
M5	1	1	1	0	0	0
M1	0	0	0	1	0	1
M4	0	0	1	1	1	1
M2	0	0	0	1	1	0

Figure-6. Part-machine matrix through Insertion (T3)

	P1	P4	P6	P3	P2	P5
M3	1	1	0	1	0	0
M5	1	1	1	0	0	0
M1	0	0	0	1	0	1
M4	0	0	1	1	1	1
M2	0	0	0	1	1	0

Exchange is another movement method that randomly selects a part from a cell, and then selects another part from another cell in order to exchange those two parts. One additional cell formation can be obtained through Exchange. This cell formation is shown in Figure 7, and referred to as T4.

Figure-7. Part-machine matrix through Exchange (T4)

	P1	P4	P3	P6	P2	P5
M3	1	1	1	0	0	0
M5	1	1	0	1	0	0
M1	0	0	1	0	0	1
M4	0	0	1	1	1	1
M2	0	0	1	0	1	0

3.4. Electromagnetism-Like Mechanism Algorithm to Obtain Solution

This step applies an electromagnetism-like mechanism algorithm to obtain the final dynamic cell formation. First it is assumed that T1, T2, T3 and T4 are the manufacturing situation in the first period, and then four initial part-machine matrices can be obtained, as shown in Figures 8, 9, 10 and 11. These four results are called T11, T21, T31, and T41. Because part-6 is not manufactured in the first period, P6' is treated as a dummy part. The group efficacy is thus calculated without P6.

Figure-8. The part-machine matrix of T_{11}

	P1	P4	P6’	P3	P2	P5
M3	1	1	0	1	0	0
M5	1	1	0	0	0	0
M1	0	0	0	1	0	1
M4	0	0	0	1	1	1
M2	0	0	0	1	1	0

Figure-9. The part-machine matrix of T_{21}

	P1	P4	P6’	P3	P2	P5
M3	1	1	0	1	0	0
M5	1	1	0	0	0	0
M1	0	0	0	1	0	1
M4	0	0	0	1	1	1
M2	0	0	0	1	1	0

Figure-10. The part-machine matrix of T_{31}

	P1	P4	P6’	P3	P2	P5
M3	1	1	0	1	0	0
M5	1	1	0	0	0	0
M1	0	0	0	1	0	1
M4	0	0	0	1	1	1
M2	0	0	0	1	1	0

Figure-11. The part-machine matrix of T_{41}

	P1	P4	P3	P6’	P2	P5
M3	1	1	1	0	0	0
M5	1	1	0	0	0	0
M1	0	0	1	0	0	1
M4	0	0	1	0	1	1
M2	0	0	1	0	1	0

Next, the group efficacies of T11, T21, T31 and T41 are calculated, respectively. T11 is used as an example, which includes all twelve operations, and the exceptional element is one, so $\varphi = \frac{1}{12}$, the empty element is two, so $\emptyset = \frac{2}{12}$, and the group efficacy of $T_{11} = \frac{1-\frac{1}{12}}{1+\frac{2}{12}} = 0.7857$.

The group efficacy of T_{21}, T_{31}, and T_{41} are calculated similarly. Thus T_{21}=0.5625, T_{31}=0.7857, T_{41}=0.6. T_1, T_2, T_3 and T_4 are used as the manufacturing situation in the second period, and then another four part-machine matrix is obtained, as shown in Figures 4, 5, 6 and 7. These four results are called T_{12}, T_{22}, T_{32} and T_{42}. The group efficacies of T_{12}, T_{22}, T_{32} and T_{42} are then calculated, such that T_{12}=0.7058, T_{22}=0.5556, T_{32}=0.6666 and T_{42}=0.5263. Finally, T_{11}, T_{21}, T_{31}, T_{41}, T_{12}, T_{22}, T_{32} and T_{42} are used to obtain four objective function values as T'_1=1.4351, T'_2=1.1132, T'_3=1.3681 and T'_4=1.0742. These four results are the points in the Electromagnetism-like Mechanism algorithm.

Because the objective function of the electromagnetism-like mechanism algorithm is a minimum problem, but the objective function of the proposed model is a maximum problem, the objective function value is converted to a negative value. Table 2 shows the results of the objective function value and the charge of each point. The total force vector of each point is then calculated, as shown in Table 3.

Table-2. The objective function value and the charge of each point

M	**T'_1**	**T'_2**	**T'_3**	**T'_4**
Min: Objective function value	−1.4351	−1.1132	−1.3681	−1.0742
$f(x^K)$-$f(x^{best})$	0	0.3219	0.067	0.3609
q^i=the charge	1	0.1572	0.6803	0.1256

Table-3. The total force vector results for each point

m	**T'_1**	**T'_2**	**T'_3**	**T'_4**
Min: Objective function value	−1.4351	−1.1132	−1.3681	−1.0742
q^i=the charge	1	0.1572	0.6803	0.1256
x^i 之 F^i		−0.4015	−9.6993	−0.8893

The final step of the algorithm is the calculation of movement according to the total force. In this step, the upper and lower bounds are set to ensure that every point only moves from 1~N. The lower bound of this study is set as -1, and the upper bound is set as -1×n. In this case, there are four solutions, so the upper bound is -1×4=-4. Table 4 shows the results of movement according to the total force.

Table-4. The movement according to the total force

M	**T'_1**	**T'_2**	**T'_3**	**T'_4**
Min: Objective function value	−1.4351	−1.1132	−1.3681	−1.0742
x^i 之 F^i		−0.4015	−9.6993	−0.8893
Value after movement	−1.4351	−1.0891	−0.5302	−1.0500

10,000 iterations are used. By 10,000 iterations, the objective function value of T'1 is still the best. Thus, it is the final cell formation, as shown in Figure 12.

Figure-12. The final part-machine diagonal matrix

	P1	**P4**	**P6**	**P3**	**P2**	**P5**
M3	1	1	0	1	0	0
M5	1	1	1	0	0	0
M1	0	0	0	1	0	1
M4	0	0	1	1	1	1
M2	0	0	0	1	1	0

4. CASE STUDY

The proposed method was implemented by Visual C++. 100 local search times were set, and then 10,000 iterations were processed from the local search. The two case studies used are from Chen (1998) and Wicks and Reasor (1999). There are two periods, seven different machines, and 11 parts in Chen (1998). Note that part-11 does not need to be manufactured in the first period. For the case of Wicks and Reasor (1999), there are three periods, 11 different machines, and 25 parts. The cell groups resulting from Chen (1998)and the proposed method are shown in Tables 4 and 5, respectively.

Table-4. The cell groups by Chen (1998)

Period	Cell No.	Machine Type	Part Type
1	1	2, 3, 6	2, 3, 5, 8
	2	4, 7	4, 7, 9
	3	1, 5	1, 6, 10
2	1	2, 3, 6	2, 3, 5, 8
	2	4, 5, 7	4, 7, 9, 11
	3	1, 5	1, 6, 10

Table-5. The final cell group by the proposed method

Period	Cell No.	Machine Type	Part Type
1	1	2, 3	2, 5, 8
	2	4, 7	4, 7, 9
	3	6, 1, 5	3, 10, 1, 6
2	1	2, 3	2, 5, 8, 11
	2	4, 7	4, 7, 9
	3	6, 1, 5	1, 3, 6, 10

The comparisons between Chen (1998) and the proposed method are summarized in Table 6

Table-6. The comparison of the first case

		Chen (1998)	The proposed method
Period 1	Exceptional element	4	4
	Empty element	6	6
	Group efficacy	0.6429	0.6429
Period 2	Exceptional element	5	6
	Empty element	10	7
	Group efficacy	0.5714	0.5938
Objective function value		1.1638	1.202

According to Table 6, the objective function value of this study is better than that of Chen (1998). Chen (1998) purchases a machine 5 to cell 2 in period 2. This decreases the exceptional element, but increases the empty element. The cases of Wicks and Reasor (1999)and the proposed method are shown in Tables 7 and 8. The comparison of the results is summarized in Table 9.

Table-7. The cell groups by Wicks and Reasor (1999)

Period	Cell No.	Machine Type	Part Type
1	1	1, 4, 6, 9, 10, 11	1, 8, 9, 16, 18, 20, 23
	2	3, 6, 11	10, 13, 17
	3	2, 5, 7, 8, 9	2, 5, 6, 12, 14, 21
2	1	1, 4, 6, 9, 10, 11	1, 3, 7, 8, 9, 16, 18, 20, 22, 23
	2	3, 5, 6, 11	4, 10, 13, 17, 19
	3	2, 5, 7, 8, 9, 10	2, 5, 6, 12, 14, 21
3	1	1, 4, 6, 9, 10, 11	1, 3, 7, 8, 9, 11, 15, 16, 18, 20, 22, 23
	2	3, 5, 6, 11	4, 10, 13, 17, 19
	3	2, 5, 7, 8, 9, 10	2, 5, 12, 21, 24, 25

The objective function of Wicks and Reasor (1999) considers the machine handling cost, machine relocation cost, machine purchasing cost, and other manufacturing cost. Wicks and Reasor (1999) consider machine handling cost to be lower than the machine purchasing cost. However, machine handling may cause production line shut-downs and increase personnel costs. If the overall cost is in the constraints, they will consider purchasing additional machine for cells. In the first period, Wicks and Reasor (1999)purchase machine-6 and machine-11 for cell 2 and machine-9 for cell 3. In the second period, they purchase machine-5 for cell 2, and machine-10 for cell 3.

Table-8. The final cell groups by the proposed method

Period	Cell No.	Machine Type	Part Type
1	1	3, 4, 9, 11	8, 10, 20
	2	5, 6, 8, 10	2, 6, 9, 14, 16, 17, 18, 23
	3	1, 2, 7	1, 5, 12, 13, 21
2	1	3, 4, 9, 11	8, 10, 20
	2	5, 6, 8, 10	2, 4, 6, 7, 9, 14, 16, 17, 18, 19, 23
	3	1, 2, 7	1, 3, 5, 12, 13, 21, 22
3	1	3, 4, 9, 11	8, 10, 11, 15, 20
	2	5, 6, 8, 10	2, 4, 7, 9, 16, 17, 18, 19, 23
	3	1, 2, 7	1, 3, 5, 12, 13, 21, 22, 24, 25

Table-9. The comparison results of the second case

		Wicks and Reasor (1999)	**The proposed method**
Period 1	Exceptional element	5	13
	Empty element	43	30
	Group efficacy	0.4353	0.411
Period 2	Exceptional element	5	17
	Empty element	63	38
	Group efficacy	0.4333	0.4211
Period 3	Exceptional element	9	19
	Empty element	74	39
	Group efficacy	0.3897	0.4257
Objective function value		1.2326	1.2503

According to Table 9, the group efficacy in the first and second periods of Wicks and Reasor (1999) is higher than that of the proposed method. However, in the third period, the group efficacy of the proposed method is higher than that of Wicks and Reasor (1999). On the other hand, the objective function value is higher than that of Wicks and Reasor (1999) in three periods. Thus, the proposed method may not be able to achieve the maximum group efficacy for each period. However, it can obtain the best objective function value in multi-period circumstances, and also maintain a balanced state in each period.

5. CONCLUSIONS AND DISCUSSIONS

In order to maximize the group efficacy for each period, and to minimize the coefficient of variation overall, the group efficacy and coefficient of variation are combined into the proposed model, in order to design a robust cell formation in a multi-period environment. The model itself is not a real number problem. Thus, the original local search must be multiplied by a local search parameter δ. The local search parameter is a value that ranges between 0 and 1. Insertion and Exchange (Belarmino *et al.*, 2001) are then applied in the local search step. However, they must meet three rules before the parts can be moved. The rules not only reduce the local search time, but also increase the solving efficiency. The resulting group efficacy for each period is compared with two existing cases. The objective function values are better than those of the two cases, both considering the purchase cost of machines. Purchasing new machines may reduce exceptional elements, but it will increase empty elements. This study suggests that if a cell formation is proper for each period, then machine relocation, machine purchase, and inter-cell and intra-cell costs can be reduced as a result.

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