A Water Flow-like Algorithm for Cell Formation, Cell Layout, and Intracellular Machine Layout Problems

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Abstract

Cell formation, cell layout, and intracellular machine layout are three basic steps in the design of cellular manufacturing system (CMS). It is important and more practical to integrate them in the design of CMS. However, it is not an easy task due to the NP-hard problem nature of each step. This paper proposes a novel approach, water flow-like algorithm (WFA), to tackle this problem. When compared with the mathematical programming approach which took 38 hours to solve problem, the proposed algorithm is able to produce optimal solution in less than one second. This shows that the proposed approach is extremely effective and efficient.

Keywords*: Water Flow-like Algorithm, Cell Formation, Cell Layout, Intracellular Machine Layout*

1. Introduction

Cellular manufacturing system (CMS) has been evolved to fulfill contemporary market demand where traditional manufacturing system was incompetent. Therefore, CMS is a solution to efficient batch type with reduced material handling costs, work-in-progress inventory, and set-up times, as well as simplified scheduling, and improved quality [1].

Although cellular manufacturing may provide great benefits, the CMS design is complex for real life problems. It has been known that the cell formation problem (CFP) with considerations of cell formation and cell layout simultaneously are NP-hard combinational problems [2]. 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 treat these problems sequentially or independently. These approaches can be classified into three main categories: mathematical programming (MP) models [3,4], heuristic/meta-heuristic solution algorithms [5-7], and similarity coefficient methods (SCM) [9-10]. Among the aforementioned heuristics/meta-heuristics, the simulated annealing (SA) and the tabu search (TS) are single-solution-agent-based algorithms. A single agent-based heuristic algorithm searches the solution space step by step through the usage of systematic or random neighborhood exploration. The genetic algorithms (GAs), however, belong to the group of multiple-solution-agent-based algorithms, which starts the optimization with a set of possible solutions, not only one possible solution. Yang and Wang [10] stated that neither the single nor the multiple agent method is agile enough to conduct an efficient and effective solution search. They hence present a water flow-like algorithm (WFA) to overcome this deficiency.

The WFA method is a dynamic-solution-agent-based algorithm. The design of the WFA method was inspired by water flowing from higher to lower levels, where a flow will split into multiple sub flows when it moves through uneven terrains. Conversely, sub flows merge when they meet at the same level. Water flow ceases and stagnates at the lowest depressions, when momentum cannot expel water out of the depressions. Water flowing is analogous to problem solving. A flow is regarded as a solution agent, the solution space of a problem is the geographical terrain, and the altitude of a flow represents the objective function value. Since the number of flows dynamically changes in this method, it is an agent population-varying method.

In this paper, we use the WFA to solve cell formation, cell layout, and intracellular machine layout. The approach is compared with the mathematical programming approach.

The remainder of this paper is organized as follows: Section 2 describes the problem definition including cell formation, cellular layout, and intracellular machine layout; Section 3 details the proposed two-stage WFA approach; Section 4 presents the use of a numerical example to illustrate the

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proposed procedure and demonstrate the effectiveness of the proposed methodology; Section 5 reports the computational results on the test problems; and Section 6 concludes the paper.

2. Problem definition

2.1. Cell formation

When parts have alternative process routings (APR) is called the generalized CFP [11]. Such as the case shown in Table 1, part P1 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. For instance, Table II provides a feasible solution to the sample problem of Table I which has two cells with machine groupings for each cell as Cell 1: (M2, M4), (P1, P3) and Cell 2: (M1, M3), (P2, P4, P5).

Table 1. A schematic diagram for cell formation

(a). Initial machine-part matrix

PN	**P1**		**P2**		**P3**		**P4**		**P5**	
PV	50		30		20		30		20	
RN	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
M1				2	2		1	1		1
M2		1	1			2				
M3	2*		2	1				2	1	
M4	1	2			1	1	2		2	

(b). Final solution of Table 1(a)

PN	**P1**	**P3**	**P2**	**P4**	**P5**
PV	50	20	30	30	20
RN	R2	R2	R2	R2	R2
M2	1	2			
M4	2	1			
M1			2	1	1
M3			1	2	

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

2.2. Cell layout

Linear double-row layout (see Figure 1) is considered in this paper. The corresponding inter-cell move distance (ICMD) between a pair of cells l and l' for this layout can be obtained by calculating the corresponding Euclidean distance, as in equation (1).

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

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'.

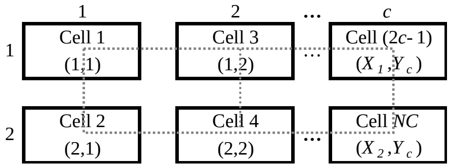


Figure 1. Linear double-row layout

2.3. Intracellular machine layout

The intra-cellular flow can be classified into four categories [12] (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 [13]. Hence, the consecutive forward flow index (CFFI) within a cell (as shown in equation (2)) was used as a measure to understand how appropriate an intracellular machine layout is.

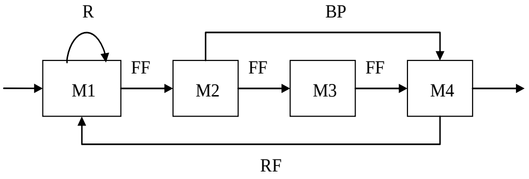


Figure 2. Intra-cellular part flow

$$\mathrm{CFFI} = \frac{N_{cff}}{N_{tf}} \tag{2}$$

Where N_{tf} is the total number of flows, N_{cff} is the number of CFF in all the cell.

3. Proposed algorithm

Due to the NP-hard combinatorial nature of ell formation and cell layout problems, 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 WFA approach is proposed in this section to solve the highly complicated CMS problem.

The design of the WFA was inspired by the natural behavior of water flowing from higher to lower levels. On the earth’s surface, a flow will split into multiple sub-flows when rugged terrains are traversed. Sub-flows, however, will merge when they arrive at the same location. Governed by gravity and driven by fluid momentum, flows can run to higher levels or run over bumps to navigate various terrains. Water flow will cease and stagnate at the locally or globally lowest depression; when the momentum left cannot expel the water out of the depression, it will stagnate at its current location. No movement is allowed until other flows merge with it or until the water evaporates into the atmosphere. When the evaporated water accumulates to some extent, it will return to the ground as several new downpour flows, such that rainfall occurs occasionally. As the solution space of a problem can be mapped to the geographical terrain, and the objective value is mapped to the altitude, each flow can then be regarded as a solution agent. Water moving to a lower position can be considered as a solution searching for the optima. Thus, the solution search process has been modeled as water flow.

The WFA algorithm consists of four primary operations: (1) flow splitting and moving, (2) flow merging, (3) water evaporation, and (4) precipitation. The pseudo-code for the general procedure for implementing the WFA is shown in Figure 3.

```
WFA_Algorithm ( )
{
    Generate an initial solution.
    WHILE(stop criterion is false)
    {
        Flow splitting and moving.
        Flow merging.
        Water evaporation.
        IF (rainfall required)
        {
            Precipitation.
            Flow Merging.
        }
        IF (new best solution found)
            Update best solution record.
    }
}
```

Figure 3. A generic framework for WFA

On the other hand, a number of SCM-based approaches have been proposed, and have been shown to produce good machine-part grouping. Thus, a two-stage HWFACF merging SCM-based clustering algorithm and WFA method is proposed. The framework of the proposed HWFACF is illustrated in Figure 4.

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.

Stage I of CFWFA:

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 WFA 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.

Stage II of HWFACF:

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 WFA 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 WFA procedure to generate a best solution (S^*) in terms of maximizing the CFFI.

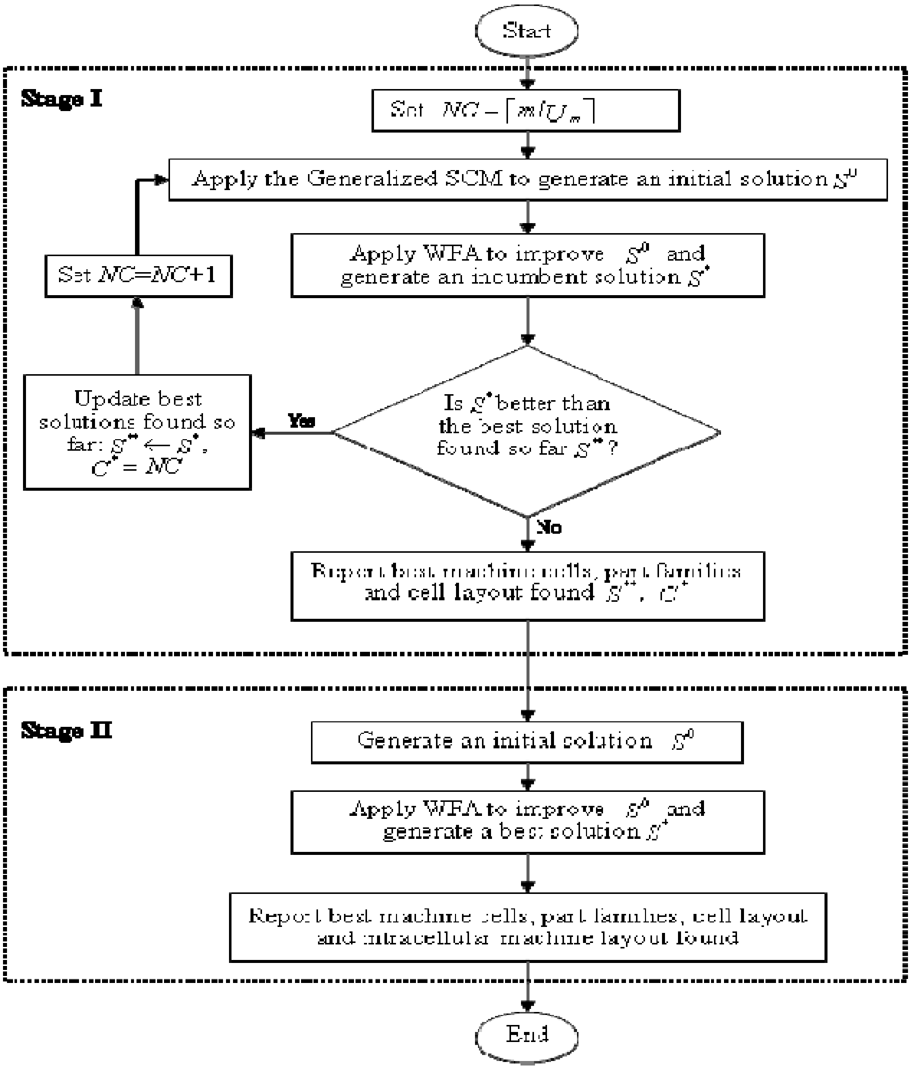


Figure 4. Framework of the proposed HWFACF

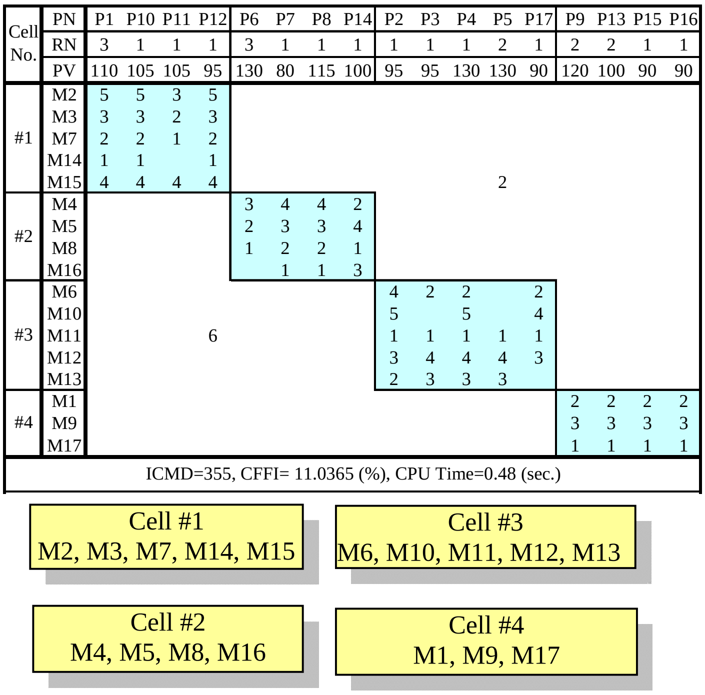
4. An illustrative example

To illustrate the effectiveness of our developed model and algorithm, a test example is demonstrated in this section. This example consists of 17 parts, 17 machines, and 35 process routings. The maximum number of machines in each cell (U_m) is limited to 5 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) 2.4GHz PC with 3.24GB RAM. The computational results for each stage are described as follows.

4.1. Stage I: Cell formation and cell layout

When parts have alternative process routings (APR) is called the generalized CFP [14]. Such as the case shown in Table I, part P1 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.

Through the proposed HWFACF in stage I, the final solution with a total ICMD of 355 and CFFI of 11.0365 % can be obtained after 0.48 second CPU time. The corresponding configuration for the cell formation, cell layout, and intracellular machine layout is displayed in Figure 5, which has four cells with machine groupings for each cell as Cell #1: (M2, M3, M7, M14, M15), Cell #2: (M4, M5, M8, M16), Cell #3: (M6, M10, M11, M12, M13), and Cell #4: (M1, M9, M17).



Cell No.	PN	P1	P10	P11	P12	P6	P7	P8	P14	P2	P3	P4	P5	P17	P9	P13	P15	P16
	RN	3	1	1	1	3	1	1	1	1	1	1	2	1	2	2	1	1
	PV	110	105	105	95	130	80	115	100	95	95	130	130	90	120	100	90	90
#1	M2	5	5	3	5													
	M3	3	3	2	3													
	M7	2	2	1	2													
	M14	1	1		1													
	M15	4	4	4	4								2					
#2	M4					3	4	4	2									
	M5					2	3	3	4									
	M8					1	2	2	1									
	M16						1	1	3									
#3	M6									4	2	2		2				
	M10									5		5		4				
	M11				6					1	1	1	1	1				
	M12									3	4	4	4	3				
	M13									2	3	3	3					
#4	M1														2	2	2	2
	M9														3	3	3	3
	M17														1	1	1	1
ICMD=355, CFFI= 11.0365 (%), CPU Time=0.48 (sec.)																		

Cell #1
M2, M3, M7, M14, M15

Cell #3
M6, M10, M11, M12, M13

Cell #2
M4, M5, M8, M16

Cell #4
M1, M9, M17

Figure 5. Final solution of stage I

In order to get the optimal solution in stage I, a branch and bound (B&B) algorithm with the Lingo 8.0 software is used. The Lingo solver status for this example is shown in Figure 6. The optimal solution (355) is obtained in 4132 seconds (1.15 hours). In contrast, our proposed HWFACF is able to find the optimal solution in 0.48 second, thus implying the superiority of HWFACF in solution efficiency.

LINGO Solver Status [LINGO1]

Solver Status
Model Class: ILP
State: Global Optimum
Objective: 0
Infeasibility: 0
Iterations: 13761093

Extended Solver Status
Solver Type B-and-B
Best Obj: 355
Obj Bound: 355
Steps: 74783
Active: 0

Variables
Total: 1924
Nonlinear: 0
Integers: 1923

Constraints
Total: 7336
Nonlinear: 0

Nonzeros
Total: 19397
Nonlinear: 0

Generator Memory Used (K)
2150

Elapsed Runtime (hh:mm:ss)
01:08:52

Update Interval: 2

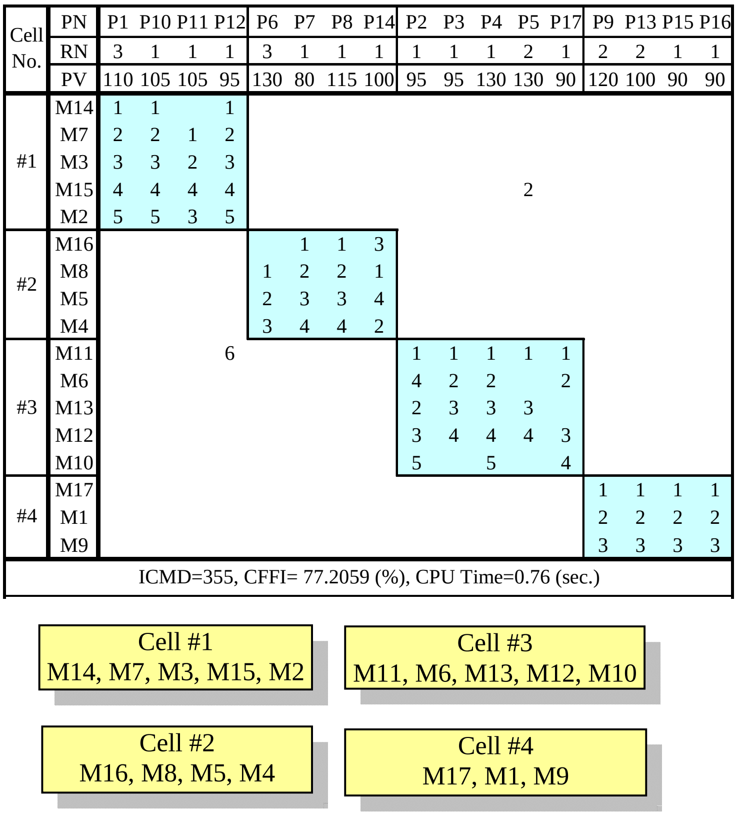
Figure 6. Lingo solver status of stage I

4.2. Stage II: Intracellular machine layout

When parts have alternative process routings (APR) is called the generalized CFP[14]. Such as the case shown in Table I, part P1 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. F

Through the proposed HWFACF in stage II, the CFFI can be improved to 77.2059(%) after 0.28 seconds CPU time. The final corresponding configuration for the cell formation, cell layout, and intracellular machine layout is displayed in Figure 7.

Figure 7. Final solution of stage II



Cell No.	PN	P1	P10	P11	P12	P6	P7	P8	P14	P2	P3	P4	P5	P17	P9	P13	P15	P16
	RN	3	1	1	1	3	1	1	1	1	1	1	2	1	2	2	1	1
	PV	110	105	105	95	130	80	115	100	95	95	130	130	90	120	100	90	90
#1	M14	1	1		1													
	M7	2	2	1	2													
	M3	3	3	2	3													
	M15	4	4	4	4								2					
	M2	5	5	3	5													
#2	M16						1	1	3									
	M8					1	2	2	1									
	M5					2	3	3	4									
	M4					3	4	4	2									
#3	M11				6					1	1	1	1	1				
	M6									4	2	2		2				
	M13									2	3	3	3					
	M12									3	4	4	4	3				
	M10									5		5		4				
#4	M17														1	1	1	1
	M1														2	2	2	2
	M9														3	3	3	3
ICMD=355, CFFI= 77.2059 (%), CPU Time=0.76 (sec.)																		

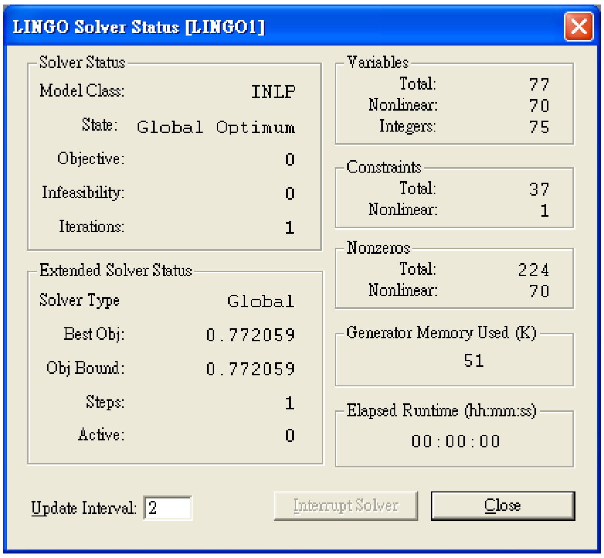
Cell #1
M14, M7, M3, M15, M2

Cell #3
M11, M6, M13, M12, M10

Cell #2
M16, M8, M5, M4

Cell #4
M17, M1, M9

In order to get the optimal solution in stage II, a branch and bound (B&B) algorithm with the Lingo 8.0 software is used. The Lingo solver status is shown in Figure 8. The optimal solution (0.772059) can be obtained in less than 1 second. In contrast, our proposed HWFACF is able to find the optimal solution in 0.28 second. This illustrates the superiority of HWFACF in solution efficacy.


LINGO Solver Status [LINGO1]

Solver Status
Model Class: INLP
State: Global Optimum
Objective: 0
Infeasibility: 0
Iterations: 1

Extended Solver Status
Solver Type Global
Best Obj: 0.772059
Obj Bound: 0.772059
Steps: 1
Active: 0

Variables
Total: 77
Nonlinear: 70
Integers: 75

Constraints
Total: 37
Nonlinear: 1

Nonzeros
Total: 224
Nonlinear: 70

Generator Memory Used (K)
51

Elapsed Runtime (hh:mm:ss)
00:00:00

Update Interval: 2

Figure 8. Lingo solver status of stage II

5. Computational results and comparisons

In order to demonstrate the effectiveness of our proposed model and methodology for cell formation and cell layout problems, six test instances 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 2. The results show that the proposed HWFACF is able to achieve global optimum for all test instances in less than 1 second. As for test instance #5, the B&B took 139078 seconds (38 hours) to find the optimal solution. In contrast, our proposed algorithm is able to produce optimal solutions in less than 1s. These findings indicate the superiority of our proposed algorithm in solution efficiency. Moreover, these results allow us to validate the quality of our proposed algorithm.

Table 2. Results comparison of HWFACF and optimal solutions by LINGO 8.0

Instance	**Source**	**Size (m×p×r)**	L_m	U_m	**LINGO 8.0 software (B&B)**				**Proposed method (HWFACF)**			
					NC	**ICMD**	**CFFI (%)**	**CPU (s)**	**NC**	**ICMD**	**CFFI (%)**	**CPU (s)**
1	[4]	9×8×20	2	6	2	105.00*	61.25*	3	2	105.00*	61.25*	0.43
2	[14]	10×10×25	2	5	2	64.00*	77.23*	11	2	64.00*	77.23*	0.34
3	[15]	12×20×26	2	5	3	29.83*	27.69*	96	3	29.83*	27.69*	0.79
4	[15]	14×20×45	2	5	3	27.07*	30.77*	58021	3	27.07*	30.77*	1.03
5	[15]	17×30×63	2	5	4	760.00*	79.74*	139078	4	760.00*	79.74*	0.90
6	[15]	18×30×59	2	7	3	33.24*	24.42*	37183	3	33.24*	24.42*	1.28

*: Global optimum

6. Conclusions

Cell formation, cell layout and intracellular machine layout are three basic steps in the design of cellular manufacturing system (CMS). Accounting these steps make the cell formation problem complex but more realistic. However, it is not an easy task due to the NP-hard problem nature. In this paper, a novel approach, water flow-like algorithm (WFA), has been designed for solving this problem.

To verify the behavior of our proposed algorithm, a set of benchmark problems have be solved using the branch and bound (B&B) algorithm implemented in the LINGO 8.0 software. This experimentation has indicated that, for all test problems, the best solutions generated by our proposed algorithm were the same as those generated with LINGO 8.0 software. Moreover, when compared with the B&B approach which took 38 hours to solve problem, our proposed algorithm was able to produce optimal solution in less than one second. These have shown that our proposed approach was extremely effective and efficient.

7. Acknowledgement

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8. References

[1] U. Wemmerlov, N. Hyer, “Research issues in cellular manufacturing,” International Journal of Production Research, vol. 25, no. 3, pp. 413–431, 1987.

[2] A. Ballakur, H.J. Steudel, “A within cell utilization based heuristic for designing cellular manufacturing systems,” International Journal of Production Research, vol. 25, no. 5, pp. 639–655, 1987.

[3] B. Elbenani, J. A. Ferland, “An exact method for solving the manufacturing cell formation problem,” International Journal of Production Research, vol. 50, no. 15, pp. 4038–4045, 2012.

[4] M.S. Jabal Ameli, J. Arkat, F. Barzinpour, “Modelling the effects of machine breakdowns in the generalized cell formation problem,” International Journal of Advanced Manufacturing Technology, vol. 39, no. 7-8, pp.838–850, 2008.

[5] Yang Yu, Li Hui, “Improved Quantum Crossover Based Genetic Algorithm For Solving Traveling Salesman Problem,” International Journal of Advancements in Computing Technology, vol. 5, no. 1, pp. 651–658, 2013.

[6] Jiang Zhenbo, Zhou Shangbo, “An Optimized Tabu Search Application on Video Object Tracking,” International Journal of Advancements in Computing Technology, vol. 4, no. 2, pp. 258–267, 2012.

[7] T.H. Wu, S.H. Chung, C.C. Chang, “A water flow-like algorithm for manufacturing cell formation problems,” European Journal of Operational Research, vol. 205, no. 2, pp. 346–360, 2010.

[8] Y. Yin, K. Yasuda, “Similarity coefficient methods applied to the cell formation problem: A taxonomy and review,” International Journal of Production Economics, vol. 101, no. 2, pp. 329–352, 2006.

[9] Y. Yin, k. Yasuda, “Similarity coefficient methods applied to the cell formation problem: a comparative investigation,” Computers and Industrial Engineering, vol. 48, no. 3, pp.471–489, 2005.

[10] F.C. Yang, Y.P. Wang, “Water flow-like algorithm for object grouping problems,” Journal of the Chinese Institute of Industrial Engineers, vol. 24, no. 6, pp. 475–488, 2007.

[11] A. Kusiak, “The generalized group technology concept,” International Journal of Production Research, vol. 25, no. 4, pp. 561–569, 1987.

[12] N.A.G. Aneke, A.S. Carrie, “A design technique for the layout of multi-product flowlines,” International Journal of Production Research, vol. 24, no. 3, pp. 471–481, 1986.

[13] Y.C. Ho, C.E. C. Lee, C.L. Moodie, “Two sequence-pattern, matching-based, flow analysis methods for multi-flowlines layout design,” International Journal of Production Research, vol. 31, no. 7, pp. 1557–1578, 1993.

[14] C.O. Kim, J.G Baek, J.K. Baek, “A two-phase heuristic algorithm for cell formation problems considering alternative part routes and machine sequences,” International Journal of Production Research, vol. 42, no. 18, pp. 3911–3927, 2004.

[15] S. Sofianopoulou, “Manufacturing cells design with alternative process plans and/or replicate machines,” International Journal of Production Research, vol. 37, no. 3, pp. 707–720, 1999.