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A New Mathematical Model for Minimization of Exceptional Load in Cellular Manufacturing Systems

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ABSTRAC: This study is devoted to the cell formation problems in cellular manufacturing systems. Starting point of this study is a paper of Mahdavi et.al. which considers only a few factors of production system. In this research, processing times and the frequencies of the parts are also considered. It is assumed that the load of each machine is known and is the multiplication of the processing times and frequencies. In this case cells are formed to achieve the higher loads inside cells. Also, the proposed model is about the case when alternative technologies are available and the objective is to maximize the loads inside cells. Besides the new model, other main contribution of this study is the computational analysis. The results show that the new model is providing acceptable solution within the logical runtimes.
Keywords: Cellular Manufacturing Systems, Cell Formation, Exceptional Load.

I. Introduction

The idea of Group Technology (GT) was first proposed in 1920's by Russians. The main concept of GT is to decompose the system into subsystems and improve each subsystem based on the various objectives to achieve the higher performance of the system. The purposes of Group Technology are best achieved in business related to small to medium batch production; these companies represent a major part of manufacturing industry. The conventional approach to this type of manufacture is to use a functional layout in the factory where production equipments are located in functional departments according to the types of manufacturing processes [1]. Typically, parts are transported from one department to another depending on the actual process plan. In this arrangement the planning of process route becomes a very complex task since a number of similar machine tools may be taken into consideration at each stage in the chain of manufacturing operations [2].

Cellular manufacturing (CM) is an application of the GT idea to design manufacturing systems. The main idea of GT is to improve productivity of manufacturing system by grouping parts and products with same features into families and forming production cells with a group of dissimilar machines and processes. Comprehensive reviews and fundamental issue in CM and GT can be found in [3-5]. In CM the main and the most researched topic is related to Cell Formation (CF). Many models were proposed to solve the CF problems. These models are developed based on the different approaches such as similarity and dissimilarity coefficients [6-8] and clustering [9, 10]. Furthermore, different adjectives function have been considered in the developed model such as operating and material handling cost [3, 11], number of voids [12, 13]. To solve CM mathematical models, different programming techniques have been developed including fuzzy programming [14-16], constraint programming [17], goal programming [18, 19].

The cell formation problem is extensively studied in the literature. The most important objective in the CMS is to minimize the number of exceptional elements which helps to reduce the number of intercellular movements. Another important objective function is to minimize the number of voids inside of the machine cells. This objective function is considered in order to increase the utilization of the machines. Nunkaew and Phruksaphanrat [20] developed a multi-objective mathematical programming technique based on perfect grouping for concurrent solving the part-family and machine-cell formation problems in CMS. New simplified mathematical expressions of exceptional and void elements are proposed, opposing conventional quadratic and absolute functions. The main objectives of their model are the minimization of both the number of exceptional elements and the number of void elements. Arkat et al. [12] presented a bi-objective mathematical model to simultaneously minimize the number of exceptional elements and the number of voids in the part machine incidence matrix. They utilized a multi-objective genetic algorithm with clustering procedure to solve their model.

Mahdavi et al. [21] proposed a new mathematical model for cell formation in CMS based on cell utilization concept. The objective of their model is to minimize the exceptional elements and number of voids in cells to achieve the higher performance of cell utilization. Furthermore, Mahdavi et al. [11] presented mathematical programming model to design CMS by minimizing holding and backorder costs, inter-cell material handling cost, machine and reconfiguration costs and hiring, firing and salary costs. Considering multi-

period production planning, dynamic system reconfiguration, duplicate machines, machine capacity, available time of workers, and worker assignment are the main advantages of their model. In another research, Mahdavi et al. [22] consider the machine flexibility concept due to utilizing multifunctional machines in the CMS. Machine-operation and part-operation are defined to introduce machine capabilities and part requirements. A novel solution approach with two phases is presented to solve the considered problem. First phase is a mathematical model proposed to define machines grouping. This model is seeking to minimize in-route machines dissimilarity. Second phase allocated to a heuristic method which assigns parts to corresponding cells.
The application of group technology concepts to the design and operation of manufacturing cells has had a major impact on improving the performance of multiproduct, moderate volume manufacturing systems. Initially, the research on manufacturing cells focused primarily on methods for identifying rational part families and machine groups using only basic processing data. However, the comprehensiveness of the problem definition and the supporting decision models has evolved over time to include many relevant organizational issues and options. Hence, different features including product demands, cell size limits, sequence of operations, multiple units of identical machines, machine capacity, or machine cost is served in the literature. In this paper a new mathematical model of CF has been proposed. To this end, a new concept i.e. exceptional load is presented as the amount of machine load which is not assigned to a formed cell. Also further information on the frequency of the parts is considered. The frequency of a part is the quantity sold from it in one time unit. The load caused by a part on a certain machine is taken into consideration both in the objective function and constraints.

II. Mathematical model

The cellular manufacturing problem which has been studied here includes the known type of parts which has to be processed on the predefined machines. Manufacturing cells are to be formed in the way that the number of the utilized machine-part pairs inside cells is maximized. Accordingly, the number of the exceptional elements will be minimized and this leads to the minimum exterior cell loads. We assumed that each part has technological alternatives i.e. it can be produced in different ways. The selection of technology is part of the cell formation as it is included in the model. In general the more technological alternatives lead to higher flexibility in the system. Here, it is also possible to introduce on the loads of machines and cells. Notice that if a machine does not take part in the production according to alternative l, then this processing time would be zero.

2.1. Assumption

The assumptions which have been considered for this model are as follows:

- The number of parts, machines and cells are known.
- Each part should be assigned to one manufacturing cell.
- Each machine should be assigned to one cell.
- The set of operations to complete a part is known.
- There are alternative technologies available for each part.
- Each part has its own number of alternatives.
- Minimum and maximum load of each machine in each cell is predefined.

2.2. Notations

Indices

i Index for parts (i=1,..,P)
j Index for machines (j=1 ,…,M)
k Index for cells (k= 1,…,C)
l Index for alternative routings (l=1,…,t_i)

Parameters

L_k lower bound of the number of machines in cell k
U_k upper bound of the number of machines in cell k
L_c minimum load of each cell
U_c maximum load of each cell
L_m minimum load of each machine
U_m maximum load of each machine
P_{ijl} Processing time of part i on machine j from alternative l
f_i frequency of the part i

Decision variables

Y_{jk} 1: if machine j is assigned to cell k; 0:Otherwise

Z_{ik} 1: if part *i* is assigned to cell *k*; 0:Otherwise

U_{il} 1: if processing of part *i* is made according to alternative *l*; 0:Otherwise

W_{ijk} 1: if part *i* and machine *j* are assigned to cell *k*; 0:Otherwise

V_{ijkl} 1: if part *i* is made on machine *j* according to alternative *l in* cell *k*; 0:Otherwise

$S_{ijkl} = U_{il} \times Y_{jk}$

The objective function is the minimization of the total exceptional load. Note that an operation is exceptional if:

- Machine *j* is assigned to cell *k*,
- Part *i* is NOT assigned to cell *k*,
- There is a process of part *i* on machine *j*.

Then the necessary and sufficient condition to be exceptional is that, $\exists k, l:$

- $Y_{jk}(1 - Z_{ik}) = 1$
- $P_{ijl} > 0,$ and
- $U_{il} = 1.$

The total exceptional load is:

$$\sum_{k=1}^{C}\sum_{i=1}^{P}\sum_{j=1}^{M} Y_{jk}(1-Z_{ik})\sum_{l=1}^{T_i} U_{il}P_{ijl}\, f_i$$
$$= -\sum_{k=1}^{C}\sum_{i=1}^{P}\sum_{j=1}^{M} W_{ijk}(\sum_{l=1}^{T_i} U_{il}P_{ijl}\, f_i) + \sum_{k=1}^{C}\sum_{i=1}^{P}\sum_{j=1}^{M} Y_{jk}(\sum_{l=1}^{T_i} U_{il}P_{ijl}\, f_i)$$

It is to be minimized. It is obvious that this objective function is non-linear. So the linearized objective function is:

$$MinZ = -\sum_{k=1}^{C}\sum_{i=1}^{P}\sum_{j=1}^{M}\sum_{l=1}^{T_i} V_{ijkl}P_{ijl}\, f_i + \sum_{k=1}^{C}\sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{l=1}^{T_i} S_{ijkl}P_{ijl}\, f_i \qquad (1)$$

Where:

$$W_{ijk} = Z_{ik} \times Y_{jk} \qquad \forall i, j, k$$
$$V_{ijkl} = W_{ijk} \times U_{il} \qquad \forall i, j, k, l$$
$$S_{ijkl} = Y_{jk} \times U_{il} \qquad \forall i, j, k, l$$

The further Constraints of the problem are as follows. Lower bound of the number of machines assigned to cells:

$$\sum_{j=1}^{M} Y_{jk} \geq L_k \qquad \forall k \qquad (2)$$

Upper bound of the number machines assigned to cells:

$$\sum_{j=1}^{M} Y_{jk} \leq U_k \qquad \forall k \qquad (3)$$

Each machine must be allocated to one cell:

$$\sum_{k=1}^{C} Y_{jk} = 1 \qquad \forall j \qquad (4)$$

Each part must be assigned to one cell:

$$\sum_{k=1}^{C} Z_{ik} = 1 \qquad \forall i \qquad (5)$$

Upper bound of the load in each cell:

$$\sum_{i=1}^{P} f_i \sum_{j=1}^{M} \sum_{l=1}^{T_i} V_{ijkl} P_{ijl} \leq U_c \qquad \forall k \qquad (6)$$

Lower bound of the load in each cell:

$$\sum_{i=1}^{P} f_i \sum_{j=1}^{M} \sum_{l=1}^{T_i} V_{ijkl} P_{ijl} \geq L_c \qquad \forall k \qquad (7)$$

Only one alternative must be selected.

$$\sum_{l=1}^{T_i} U_{il} = 1 \qquad \forall i \qquad (8)$$

Lower bound of the load for each machine:

$$\sum_{i=1}^{P} \sum_{l=1}^{T_i} U_{il} P_{ijl} f_i \geq L_m \qquad \forall j \qquad (9)$$

Upper bound of load for each machine:

$$\sum_{i=1}^{P} \sum_{l=1}^{T_i} U_{il} P_{ijl} f_i \leq U_m \qquad \forall j \qquad (10)$$

The linearization of the nonlinear terms is made as: If both Z_{ik} and Y_{jk} are one, then W_{ijk} must be equal to one:

$$W_{ijk} - Z_{ik} - Y_{jk} + 1.5 \geq 0 \qquad \forall i, j, k \qquad (11)$$

If at least one of Z_{ik} and Y_{jk} is zero, then W_{ijk} must be zero:

$$1.5\ W_{ijk} - Z_{ik} - Y_{jk} \leq 0 \qquad \forall i, j, k \qquad (12)$$

If both W_{ijk} and U_{il} are one, then V_{ijkl} must be equal to one:

$$V_{ijkl} - W_{ijk} - U_{il} + 1.5 \geq 0 \qquad \forall i, j, k, l \qquad (13)$$

If at least one of W_{ijk} and U_{il} is zero, then V_{ijkl} must be zero:

$$1.5\ V_{ijkl} - W_{ijk} - U_{il} \leq 0 \qquad \forall i, j, k, l \qquad (14)$$

Further on if both Y_{jk} and U_{il} are one, then S_{ijkl} must be equal to one:

$$S_{ijkl} - Y_{jk} - U_{il} + 1.5 \geq 0 \qquad \forall i, j, k, l \qquad (15)$$

If at least one of Y_{jk} and U_{il} is zero, then S_{ijkl} must be zero:

$$1.5\ S_{ijkl} - Y_{jk} - U_{il} \leq 0 \qquad \forall i, j, k, l \qquad (16)$$

III. EXPERIMENTS AND ANALYSIS OF THE RESULTS

In this section the results of several experiments are analyzed. All the experiments are performed on 20 identical computers (Pentium D, 3.00 GHZ, 960 MB RAM) in the Department of Industrial Engineering of Eastern Mediterranean University.

3.1 Coding

The solver package used for these experiments is extended LINGO 9.0(LINDO 2005). This software uses branch and bound algorithm. It also uses heuristic methods to find a feasible solution and the selected heuristic method might change for a same problem in different experiments. Therefore, having a different solution for the same problem under same circumstances is also possible.

3.2 The experiment

The suggested model is developed to solve the problems with alternative technologies. The experiment is performed by a randomly generated numerical problem having 10 parts, 10 machines, and 3 cells. There are two technological alternatives available for each part. The frequencies are random numbers between 10 and 50. The technological alternatives differ in production routes and processing times, which are random numbers between 1 and 10. Data are shown in the sequence described above which means, table (1) is showing the input data for the case of solving the problem by considering the first alternative only, table (2) is related to the solving for the second alternative, and table (3) is the complete table of information about all alternatives and the frequencies.

The experimental procedure compares the results of three cases:

- Case 1: each part has the first technological alternative,
- Case 2: each part has the second technological alternative,
- Case 3: each part has both technological alternatives.

The corresponding results are shown in Table (4), where in this table:

- 1, stands for the number of utilized pairs inside the cells,
- 2, is the number of un-utilized pairs inside the cells, i.e. the number of voids,
- 3, is the number of exceptional elements,
- 4, is the total the number of voids and exceptional elements, and,
- 5, is a duration that the solver needs to find the optimal solution. (LINGO was stopped by the time limit of 3600 seconds.)

The detailed information about the solutions related to these three cases can be found in tables (5), (6) and (7) of Appendix.

It should be mentioned that case one and case two are two randomly selected problems from all possible combinations of the alternatives which are 1024 problems. Table (8) shows the alternatives selected by the third model.

However, the overall load inside cells of case three is not higher than cases one and two, it can be stated that this solution is a better solution due to the consideration of more factors like best alternative selection to reduce the exceptional loads and the minimum number of un-utilized pairs inside of the cells. Tables (9), (10), (11) in Appendix are the formed part/machine matrices for all the three cases.

IV. CONCLUDING REMARKS

This study is devoted to the cell formation problems in cellular manufacturing systems. Starting point of this study is a paper of Mahdavi et.al. [21] which considers only a few factors of production system. In this research, processing times and the frequencies of the parts are also considered. It is assumed that the load of each machine is known and is the multiplication of the processing times and frequencies. In this case cells are formed to achieve the higher loads inside cells. Also, the proposed model is about the case when alternative technologies are available and the objective is to maximize the loads inside cells. Besides the new model, other main contribution of this study is the computational analysis. The results show that the new model is providing better solution within the logical and acceptable runtimes.

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Appendix

Table (1).

	1	2	3	4	5	6	7	8	9	10	Freq.
1	4	0	0	0	0	0	0	10	0	0	21
2	0	1	2	7	0	0	0	0	0	8	45
3	0	0	6	10	0	0	8	0	0	10	43
4	1	0	3	0	5	3	0	0	3	0	16
5	0	0	0	7	0	0	0	6	3	6	31
6	10	5	0	0	7	0	0	3	9	0	45
7	0	7	0	3	0	0	5	9	0	0	10
8	0	0	8	0	9	10	8	0	0	0	35
9	0	9	10	0	8	3	0	3	5	0	15
10	0	0	6	0	9	10	0	0	6	0	11

Table (2).

	1	2	3	4	5	6	7	8	9	10	Freq.
1	0	0	0	3	1	0	0	7	2	0	21
2	0	0	0	2	2	2	0	0	0	0	45
3	0	0	1	1	0	0	0	0	3	7	43
4	5	6	3	10	3	8	0	0	0	0	16
5	5	3	0	8	0	9	0	4	0	3	31
6	0	0	6	3	0	5	9	9	0	0	45
7	6	1	4	7	0	0	0	0	0	0	10
8	0	0	0	10	1	0	0	5	6	0	35
9	0	0	9	7	0	7	0	0	9	0	15
10	0	0	2	0	9	0	0	0	0	0	11

Table (3).

	1	2	3	4	5	6	7	8	9	10	Freq.
1	4	0	0	0	0	0	0	10	0	0	21
	0	0	0	3	1	0	0	7	2	0	
2	0	1	2	7	0	0	0	0	0	8	45
	0	0	0	2	2	2	0	0	0	0	
3	0	0	6	10	0	0	8	0	0	10	43
	0	0	1	1	0	0	0	0	3	7	
4	1	0	3	0	5	3	0	0	3	0	16
	5	6	3	10	3	8	0	0	0	0	
5	0	0	0	7	0	0	0	6	3	6	31
	5	3	0	8	0	9	0	4	0	3	
6	10	5	0	0	7	0	0	3	9	0	45
	0	0	6	3	0	5	9	9	0	0	
7	0	7	0	3	0	0	5	9	0	0	10
	6	1	4	7	0	0	0	0	0	0	
8	0	0	8	0	9	10	8	0	0	0	35
	0	0	0	10	1	0	0	5	6	0	
9	0	9	10	0	8	3	0	3	5	0	15
	0	0	9	7	0	7	0	0	9	0	
10	0	0	6	0	9	10	0	0	6	0	11
	0	0	2	0	9	0	0	0	0	0	

Table (4).

	1	2	3	4	5
Case 1	27	21	14	35	47

Case 2	28	24	14	38	30
Case 3	27	10	14	24	3600

Table (5).

Cell number	Machine number	Load Inside Cell	Load Outside Cell	Difference
1	1	450	100	350
1	9	405	282	123
Total Load		855	382	473
2	3	892	0	892
2	4	962	30	932
2	5	614	315	299
2	6	553	0	553
2	7	624	50	574
2	10	976	0	976
Total Load		4621	395	4226
3	2	70	405	-335
3	8	300	366	-66
Total Load		370	771	-401
Overall load		5846	1548	4298

Table (6).

Cell number	Machine number	Load Inside Cell	Load Outside Cell	Difference
1	1	295	0	295
1	3	493	65	428
1	4	1221	43	1178
1	6	827	0	827
1	7	405	0	405
1	8	851	0	851
Total Load		4092	108	3984
2	9	129	387	-258
2	10	301	93	208
Total Load		430	480	-50
3	2	0	199	-199
3	5	99	194	-95
Total Load		99	393	-294
Overall load		4621	981	3640

Table (7).

Cell number	Machine number	Load Inside Cell	Load Outside Cell	Difference
1	1	510	16	494
1	2	235	0	235
1	9	405	447	-42
Total Load		1150	463	687
2	3	485	83	402
2	5	584	336	248
2	6	593	0	593
2	7	280	0	280
Total Load		1942	419	1523
3	4	323	265	58
3	8	333	135	198
3	10	487	0	487
Total Load		1143	400	743

Overall load		4235	1282	2953

Table (8).

Part	1	2	3		5	6	7	8	9	10
Alternative	2	2	2	1	1	1	2	1	2	2

Table (9).

	1	9	3	4	5	6	7	10	2	8
6	450	405	0	0	315	0	0	0	225	135
2	0	0	90	315	0	0	0	360	45	0
3	0	0	258	430	0	0	344	430	0	0
4	16	48	48	0	80	48	0	0	0	0
5	0	93	0	217	0	0	0	186	0	186
8	0	0	280	0	315	350	280	0	0	0
9	0	75	150	0	120	45	0	0	135	45
10	0	66	66	0	99	110	0	0	0	0
1	84	0	0	0	0	0	0	0	0	210
7	0	0	0	30	0	0	50	0	70	90

Table (10).

	1	3	4	6	7	8	9	10	2	5
1	0	0	63	0	0	147	42	0	0	21
2	0	0	90	90	0	0	0	0	0	90
4	80	48	160	128	0	0	0	0	96	48
5	155	0	248	279	0	124	0	93	93	0
6	0	270	135	225	405	405	0	0	0	0
7	60	40	70	0	0	0	0	0	10	0
8	0	0	350	0	0	175	210	0	0	35
9	0	135	105	105	0	0	135	0	0	0
3	0	43	43	0	0	0	129	301	0	0
10	0	22	0	0	0	0	0	0	0	99

Table (11).

	1	2	9	3	5	6	7	4	8	10
6	450	225	405	0	315	0	0	0	135	0
7	60	10	0	40	0	0	0	70	0	0
2	0	0	0	0	90	90	0	90	0	0
4	16	0	48	48	80	48	0	0	0	0
8	0	0	0	280	315	350	280	0	0	0
9	0	0	135	135	0	105	0	105	0	0
10	0	0	0	22	99	0	0	0	0	0
1	0	0	42	0	21	0	0	63	147	0
3	0	0	129	43	0	0	0	43	0	301
5	0	0	93	0	0	0	0	217	186	186