Manufacturing Cell Design for Changing Demands of the Automobile Industry

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ABSTRACT

Small job shops which were earlier catering as ancillaries to the larger factories, have emerged as real profit centers by earning their livelihood through "flexible production" in accordance with the variety of demand. This situation has suggested for an essential change in the design and operation of manufacturing set-ups. Managers have realized that running the large units as an optimized and effective combination of a number of smaller units will make the industry flexible, according to the demand changes. This concept is technically explained in the form of Cellular Manufacturing, and is therefore the right approach for such situation. This paper, while taking reference of an Automotive Manufacturing Unit in Pithampur (MP), presents a model for cell formation that allows for period-to-period demand variability and considers the size of the cell when determining the cost to process each part. The model also allows the composition of a cell to be changed from period to period. Five heuristic procedures are presented and tested. The best procedure is also compared with two other traditional approaches. The results show that considering demand variability and changing the cell composition during the planning horizon can result in better solutions.

I. INTRODUCTION

Cellular manufacturing (CM) is a manufacturing application of the group technology philosophy. Products or parts that have similar process requirements are grouped together to form part families, as described by Srinivasan *et.al* [16] and Taboun *et.al* [17]. The processes needed to produce a family are then dedicated and arranged in a way that facilitates efficient materials flow, as also depicted by Adil and Rajamani [1]. This enables the family to be manufactured with rapid throughput times and a low unit cost while maintaining a reasonable level of equipment utilization.

This research is motivated through several visits to factories in Pithampur (MP) region that have implemented or in process of implementing cellular layouts. A key finding of these visits is that companies that implement cellular manufacturing constantly adapt to long-term changes in demand. These changes in demand can occur for a variety of reasons including: growth and decline of demand for a product, new customers or lost customers, new products or the elimination of old products, new contracts or contracts that expire and are not renewed. A second key finding during these visits is that the cellular layouts contained some dedicated and ''small'' (in terms of number of machines) cells with other flexible and larger cells. This finding suggests that these companies were simultaneously striving to increase operational efficiency (through dedicated cells) while at the same time efficiently using capital equipment to provide customers with product variety.

Long-term changes in demand, as mentioned by Wicks & Reasor [22], can cause processes in some cells to be inadequate to meet demand and processes in other cells to be underutilized. There are several ways to solve these problems, however, each one of these has its own associated cost, as indicated below:-

Table 1

	Probable Solution	Associated Cost
1	The cell assignments of some parts can be changed.	Training and organization costs.
2	New equipment can be purchased and added to a cell to meet increased demand requirements.	Capital investment.
3	Equipment that is underutilized in a cell can be moved to a cell where demand requirements for the equipment are higher.	Costs to move equipment and reorganize the cells.
4	Equipment that is underutilized can be sold or scrapped.	Costs to remove the equipment and reorganize the cell.

Having a lot of research carried out in the past such as Askin, Selim & Vakharia [2], Schaller [12], Singh [15], Wemmerlo & Johnson [21], "flexible design as per demand changes" attracted lesser attention due to obvious reasons. The present study proposes an integer model that considers part reallocation or equipment reallocation between cells as alternatives for the redesign of a cellular manufacturing system to handle long-term demand changes. The model also considers the production cost within a cell based on the number of machines assigned to the cell. In the next section this model is presented.

II.MODEL FOR CELL FORMATION

A model is proposed, in this section, to design a cell system that responds to long-term changes in demand. The model minimizes the total of the amortized machine costs, the cost of relocating equipment, and the cost of producing parts. A key attribute of this model is that the cost of producing a part within a given cell is based on a stepwise linear function. This function assumes that the cost of producing a part within a cell is linear as long as the number of machines in the cell is within a certain interval. As the size of the cell increases beyond a certain threshold there is a break in the function and a stepwise increase in the cost of production within the cell, as depicted by Sankaran and Kasilingam [11]. The reason for including this step function is that a small cell that only contains a few machines has a high degree of focus and will minimize production costs. As machines are added the size of the cell increases and the cell's focus is lost and production costs within the cell increases. Some of the factors that lead to increased costs are material handling cost, setup cost, work-in-process inventory cost, and scheduling and coordination costs.

These costs are assumed to be relatively constant for a range on the number of machines to be included in a cell so a series of break points, each represents an upper limit for a range, is associated with a production cost level. The following notation is used in the model:

(a) Indexes

- p part index ($p = 1,. . . ,P$) where P is the number of parts
- k cell index ($k = 1,. . . ,K$) where K is the number of cells
- j machine type index ($j = 1,. . . ,J$) where J is the number of machine types
- t period index ($t = 1,. . . ,T$) where T is the number of periods considered
- n index for cell size bounds ($n = 1,. . . ,N$) where N is the number of cell size bounds

(b) Parameters

- C_{pn} cost to produce one unit of part p in a cell of size n
- UB_n upper bound in terms of number of machines for cell size n
- S_j set of parts requiring machine type j
- t_{pj} processing time of part p on machine type j
- G_j time available for one machine of type j
- A_j amortized cost per period of a machine of type j
- D_{pt} demand for part p in period t
- MT_j cost to move one machine of type j into a cell
- MF_j cost to remove one machine of type j from a cell

(c) Variables

- X_{pktn} = 1 if part p is assigned to cell k of size n in period t, 0 otherwise
- F_{jkt} the number of machines of type j removed from cell k in period t
- T_{jkt} the number of machines of type j moved to cell k in period t
- Z_{ktn} = 1 if cell k is of size n in period t, 0 otherwise
- Y_{jkt} number of machines of type j assigned to cell k in period t

(d) Proposed Model

$$\text{Minimize } Z= \sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{n=1}^{N} C_{pn} \text{ x } D_{pt} \text{ x } X_{pktn} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} A_j \text{ x } Y_{jkt} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=2}^{T} MT_j \text{ x } T_{jkt} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=2}^{T} MF_j \text{ x } F_{jkt} \quad \text{.....................(1)}$$

Subject to

$$\sum_{n=1}^{N} Z_{ktn} \leq 1 \text{ for all k and t} \quad \text{..................(2)}$$

$$Y_{jkt-1} + T_{jkt} - F_{jkt} - Y_{jkt} = 0 \text{ for all j, k and t=2,…,T} \quad \text{.....................(3)}$$

$$\sum_{k=1}^{K}\sum_{n=1}^{N} X_{pktn} = 1 \text{ for all p and t} \quad \text{.....................(4)}$$

$$\sum_{p\in S_j}\sum_{n=1}^{N} t_{pj} \text{ x } D_{pt} \text{ x } X_{pktn} \leq G_j \text{ x } Y_{jkt} \text{ for all j,k and t} \quad \text{.....................(5)}$$

$$\sum_{j=1}^{J} Y_{jkt} \leq UB_n \text{ x } Z_{ktn} \text{ for all k and t} \quad \text{.....................(6)}$$

$$Z_{ktn} \in \{0,1\} \text{ for all k,t and n} \quad \text{.....................(7)}$$

$X_{pktn} \in \{0,1\}$ for all k,t and n

…………………(8)

Y_{jkt} is integer for all j,k and t

…………………(9)

Eq. (1) is the objective function for the model. The first term in (1) is the production cost of the parts. The second term in (1) is the total amortized cost of machines. The third and fourth terms are the cost of relocating machines into and out of cells each period. Constraint set (2) forces each cell to be of a single size during each period. Constraint set (3) determines how many machines of each type were relocated into or out of each cell during each period. Constraint set (4) ensures that the demand for each part is met in each period. Constraint set (5) is the capacity constraints for each machine type in each cell during each period. Constraint set (6) establishes the size of each cell during each period based on the number of machines assigned to the cell. Constraint set (7) requires the cell size variables to be 0 or 1 for each period. Constraint set (8) requires the part assignment variables to be 0 or 1, and constraint set (9) requires the number of machines of each type assigned to each cell during each period to be integer.

Since the model is a combinatorial optimization problem and is NP-complete it would be difficult to solve even relatively small problems. Therefore, in the next section heuristic procedures that generate solutions for the model are presented.

III. HEURISTIC PROCEDURES

Five heuristic procedures for the model are presented in this section. The first procedure starts with each part in its own cell and then attempts to combine cells to reduce costs. This procedure is referred to as CB.

The other four procedures use tabu searches, as mentioned by Glover [6], [7], to generate solutions for the problem.

(a) CB procedure

The CB procedure assigns each part to a single cell over the entire planning horizon. The procedure has two phases. A dedicated cell is created for each part in the first phase. By dedicating each cell to a single part production cost is minimized but the cost of machines needed to create the cells is relatively high.

Cells are combined in the procedure's second phase. Combining cells and processing multiple parts in a single cell reduces the cost of the machines required but increases cell size and hence production costs. During this phase several iterations are performed. An iteration of the procedure checks the cost of combining every possible pair of cells. If the cost of a solution cannot be reduced by combining a pair of cells then the procedure stops and the current solution is implemented. If the procedure is successful in finding one or more pair of cells that if combined would reduce the cost of the solution then the pair of cells that when combined would result in the largest cost reduction are combined. To combine a pair of cells the parts assigned to the old cells are reassigned to a new cell and the number of machines of each type required to process the parts are assigned to the new cell. This solution then becomes the current solution and another iteration is attempted.

This procedure attempts to balance the cost of machines used with the cost of producing the parts within the cells. A weakness of this procedure is that a part is never reassigned to another cell during the planning horizon. By allowing a part to be assigned to different cells in different periods it may be possible to reduce both the cost of production and the cost of the machines. The tabu search procedures described in the following section attempt to address this problem.

(b) Tabu search procedures

Four procedures that use a tabu search were developed for the problem. Key decisions needed to specify a tabu search for the problem described in this paper are:

(i) How is an initial starting solution developed?
(ii) What is the neighborhood of an existing solution?
(iii) How many moves are retained in the tabu list?
(iv) What are the criteria for stopping the procedure?

The first tabu search procedure is referred to as TSH1. This procedure starts with an initial solution that assigns each part to its own cell during each period (this is the same initial solution that was used in the CB procedure). The following paragraphs describe key aspects of this procedure.

(c) Solution defined.

In the context of the problem presented in this paper a feasible solution P consists of an assignment for each part to a cell for each period. Once a solution P has been defined it is easy to calculate the cost associated with the solution. First the number of machines of each type required in each cell during each period to satisfy constraint set (5) is calculated based on the parts assigned to the cell. This calculation also provides the size of each cell by adding up the total number of machines assigned to each cell so the cost of production can be calculated. After the number and types of machines for each cell have been calculated the total cost of machines and the cost of moving machines from one cell to another can be calculated.
Let Z(P) = the total cost of solution P.

(d) Move defined.

A move is defined as moving from solution P to solution P0. Solution P0 is created by assigning one part to a cell during one period that is different from its assignment in P and retaining all of the other cell assignments for each of the parts that were used in P.

(e) Neighborhood of an existing solution defined.

Let N (P) = the neighborhood of a solution P. N (P) = {P0: where P0 is a solution obtained from P by changing the assignment in P of one part during one period from its existing cell to another cell}. If there are K cells, P parts, and T periods then there are T * P * (K _ 1) possible neighboring solutions for a given set of part-period assignments. Some of the potential solutions may be eliminated because they are on the tabu list.

(f) Tabu list.

The value of a move is defined as the difference in total costs of the solutions after and before a move. An improving move has a negative value. An iteration of the search is completed when the entire neighborhood of a current solution has been evaluated and the move with the smallest move value identified is implemented. In order to avoid returning to local optimums a tabu list is used to forbid a number of recent moves. Each time a move is implemented the part, period, and the new cell assignment is retained as an entry in the tabu list. The number of entries in the tabu list is referred to as the tabu list size. Each time an iteration is performed the move implemented is added to the tabu list as the newest entry and the oldest entry is discarded from the list. When evaluating the neighborhood of a solution a move will be discarded if it is on the tabu list with the following exception. If a move will result in an improved incumbent value then the move will be implemented if it is the best move within the neighborhood of the current solution even if it is on the tabu list.

(g) Tabu list sizes.

The tabu searches used in this research use variable sized tabu lists. When variable sized tabu lists are used the size of a tabu list remains the same until a number of iterations pass with no improvement in the incumbent value then the size of the tabu list changes and the process repeats itself. The purpose of dynamically changing the tabu list size is to intensify or diversify the search in the current search region, similar to the work done by Chen [3]. Decreasing the tabu list size intensifies the search and increasing the list size diversifies the search. Three list sizes were used in the tabu search. This allows for a relatively intense search, a diverse search, and a search that is not relatively intense or diverse. After some experimentation the following three sets of tabu list sizes and number of iterations without improvement parameters were chosen (P is the number of parts to be produced).

Set	Tabu list size	# of Iter. W/O Imp.
1	P/2	P * 2
2	P * 5	P * 3
3	P	P* 5

(h) Stopping criteria. The procedure tries each of the tabu list sizes. If any of the three attempts results in an improved solution then the process is started again. If the tabu list sizes each fail to produce an improved solution then the procedure stops.

(i) Tabu search procedure (TSH1). In the following procedure the variable ts indicates the tabu list size that is being used, iter is a count of the number of iterations that have passed without finding an improved solution, no_improvement is the number of iterations that are allowed without finding an improved solution before a switch to another tabu list size is performed, improved is an indicator of whether or not an improved solution was found during the current cycle of the procedure (a cycle of the procedure consists of steps 2 through 5), Z (P) is the total cost associated with solution P, Z* is the total cost of the best solution found, and P* is the best solution found.

Input: a solution P developed by initially dedicating a cell to each part for all time periods. Initially, P* is equal to P and Z* is set equal to Z (P).

Step 1. Set improved = 0. Enter step 2.
Step 2. Set ts = 1 and update the tabu list size; set iter = 0.
Step 3. While iter < no_improvement do neighborhood.
Step 4. Set ts = ts + 1; update the tabu list size.
Step 5. If ts < 4 then set iter = 0 and repeat step 3; otherwise enter step 6.
Step 6. If improved = 1 then repeat step 2; otherwise stop the search and accept the best solution.

In step 3 of the tabu search procedure the sub-procedure neighborhood is used to evaluate the neighborhood of the current solution. In the sub-procedure the variable move_part indicates the part that will have a cell assignment changed for one time period, move_per is the period that the part will have its cell assignment changed, new_cell_ass is the new cell assignment for the current move, and N_mincost is the minimum cost found in the neighborhood of the current solution. The variable Xpkt indicates whether or not part p is assigned to cell k during period t (Xpkt = 1, if it is and 0 otherwise). Also, K is the number of cells, P is the number of parts to be produced, and T is the number of periods.

(j) Neighborhood

Input: a current solution P that assigns each part to a cell during each period.

Step 1. Set iter = iter + 1, move_part = 0, move_per = 0, new_cell_ass = 0, N_mincost = M (M is a very large number), p = 1, t = 1, and k = 1. Enter step 2.

Step 2. If Xpkt 5 1 then create a solution P0 from P by changing the cell assignment of part p during period t to cell k and leaving all the other cell assignments the same as P; enter step 3; otherwise step 9.

Step 3. Set Z (P0) = the total cost of the solution P0; enter step 4.

Step 4. If Z (P0) < Z* then enter step 5; otherwise enter step 6.

Step 5. Set iter = 0; Set N_mincost = Z (P0), move_part = p, move_per = t, new_cell_ass = k, update the best total cost found (Z* = Z (P0)), update the best solution found (P* = P0). Enter step 8.

Step 6. If Z (P0) < N_mincost enter step 7; otherwise enter step 9.

Step 7. Check to see if the assignment is on the tabu list; if the assignment is not on the tabu list enter step 8; otherwise enter step 9.

Step 8. Set move_part = p, move_per = t, move_cell = k, N_mincost = Z (P0). Enter step 9.

Step 9. Set k = k + 1; if k 6 K then repeat step 2; otherwise enter step 10.

Step 10. Set t = t + 1; if t 6 T then repeat step 2; otherwise enter step 11.

Step 11. Set p = p + 1; if p 6 P then repeat step 2; otherwise enter step 12.

Step 12. Update the tabu list with the move that was found; Update solution P by implementing the move that was found; stop.

(k) **Second tabu search procedure (TSH2)**. This procedure differs from TSH1 in that two phases of a tabu search are used. The same initial starting solution is used in TSH2 as was used in TSH1. In the first phase of TSH2 a part is assigned to the same cell for all periods. Therefore the definition of the neighborhood of a solution is to change the cell assignment of one part from its existing cell to another cell. The second phase of this procedure uses the best solution found in phase one as the starting solution and uses the tabu search defined in TSH1 in an attempt to improve upon the solution.

(l) **Third tabu search procedure (TSH3)**. This procedure is the same as the TSH1 procedure with the exception of the initial solution that is used by the tabu search. In this procedure the CB procedure is first used to generate an initial solution for the tabu search.

(m) **Fourth tabu search procedure (TSH4)**. This procedure is the same as the TSH2 procedure with the exception of the initial solution that is used by the tabu search. In this procedure the CB procedure is first used to generate an initial solution for the tabu search. The next section describes the data that were used to test the procedures as well as the results of the test.

IV. DESCRIPTION OF THE DATA AND RESULTS

(a) Description of data

The heuristic procedures were tested using the data sets described in this section. The data elements required for each problem are: the set of operations required to produce each part, the machine type and processing time required for each operation, the demand in units for each part during each period, the time one unit of each machine type is available during the year, the amortized cost per year of one unit of each machine type, the cost to move one unit of a machine type into a cell, the cost to move one unit of a machine type from a cell, the cost to process a part within a cell of a given cell size, and upper bounds in terms of number of machines for each cell size.

Sixteen problems were used in the test. The operations sequences and machine types for the set of parts used in each problem were obtained from problems previously used in the literature. Table 2 shows the reference for each problem, the number of parts in the problem, and the number of machine types included in the problem.
Number of parts and machines types for the data set

Table 2

Problem	Reference	Number of parts (I)	Number of machine types (J)
1	Mahdavi, Shirazi & Paydar (2008)	8	20
2	Yang and Jenn-Hwai (2008)	9	9
3	Kao and Fu (2006)	7	5
4	Sankaran and Kasilingam (1993)	8	6
5	Stanfel (1985)	9	4
6	Stanfel (1985)	11	6
7	Stanfel (1985)	12	7
8	Stanfel (1985)	18	13
9	Askin, Selim, and Vakharia (1997)	19	10
11	De Witte (1980)	19	12
12	Chandrasekharan and Rajagopalan (1986)	20	8
13	Srinivasan et al. (1990)	20	10
14	Seifoddini (1989)	22	11
15	Stanfel (1985)	24	7
16	Askin and Subramanian (1987)	24	14
17	Srinivasan et al. (1990)	30	12

Processing times and unit demands were randomly generated. For each machine type required by each part, a processing time was generated using a uniform distribution with parameters [1, 10] rounded to the nearest integer. The unit demand for the first period for each part was generated using a uniform distribution with parameters [100, 4000] rounded to the nearest integer. To obtain the demand for each of the remaining periods a percentage increase or decrease was randomly generated for each part and applied to the most recent period's demand for the part to obtain the next period's demand for the part. The percent increase or decrease for each part for each period was generated using a uniform distribution with parameters [_50, 50] rounded to the nearest 10%.

Each machine of a machine type is available for processing 35,000 time units per year. The annual amortization cost of a machine of each type was randomly generated. For each type the cost was generated using a uniform distribution with parameters [30,72] rounded to the nearest integer and then the result was multiplied by Rs. 50,000. The cost to move one machine of a type into a cell was set equal to 25% of the annual amortization cost of the type. The cost to move one machine of a type out of a cell was set equal 0.
The cost to process a part within a cell for each cell size and the ranges in terms of number of machines associated with each cell size were:

# of Machines	Cost of processing one unit (Rs.)
Wk ≤ 3	0
3 < Wk ≤ 5	250
5 < Wk ≤ 8	500
8 < Wk ≤ 12	750
12 < Wk ≤ 24	1250
24 < Wk	1500

(courtesy – Industrial Engg Deptt, An Automobile Industry in Pithampur)

where W k = ∑ PJ j¼1 Y jk for k = 1,. . . ,K.

(b) Performance measures

The procedures were used to generate solutions for each problem. An IBM Thinkpad (with Intel Centrino Processor) was used to perform the procedures. The cost of each procedure's solution and the time in seconds required by each procedure to generate the solution were recorded. The performance measures used to evaluate the procedures are the time in seconds required to generate a solution and the percent the cost of a solution exceeds the cost of the best solution generated for the problem. Let ZH = the cost of the solution generated by heuristic H for the problem, Zb = the best cost of any of the solutions generated by the heuristic procedures for the problem. Percent over best solution (% vs. Best) = (ZH - Zb)/Zb * 100.

Times required by each procedure to generate a solution (in sec.)

Table 3

Problem	**Procedure**				
	CB	**TSH1**	**TSH2**	**TSH3**	**TSH4**
1	0.00	0.55	0.49	0.17	0.22
2	0.00	0.16	0.66	0.16	0.28
3	0.00	2.37	1.58	0.45	0.76
4	0.07	2.08	2.16	0.77	1.10
5	0.16	17.44	7.90	1.06	1.70
6	0.23	12.81	8.08	0.99	1.70
7	0.23	15.71	9.77	2.47	3.03
8	0.23	12.14	10.05	4.89	5.99
9	0.17	10.61	11.04	3.25	3.57
10	0.13	6.32	12.75	3.35	8.24
11	0.32	15.66	14.00	2.96	4.67
12	0.28	3.67	24.50	3.68	6.66
13	0.45	17.23	23.77	7.35	7.09
14	0.66	34.60	33.84	6.38	14.07
15	0.94	58.88	62.34	13.95	16.59
16	1.37	98.43	102.71	29.82	18.74

(c) Summary of results

(i) CB procedure required the least amount of time to generate a solution for every problem. This procedure required less than 2 s to generate a solution for each problem.

(ii) All four of the tabu search procedures were less efficient than the CB procedure in terms of the processing time required for each problem. TSH1 and TSH2 required more time in general than TSH3 and TSH4 and either TSH1 or TSH2 required the most time for every problem.

(iii) Cell formation cannot be frequently performed and the layout chosen has a large impact on future costs therefore the time required by all of the procedures is acceptable.

(iv) For problems that are much larger than the problems used in this test the time required by the tabu search procedures may become excessive especially when considering the need for sensitivity analysis (changing costs, demands, etc.).

(v) Each procedure requires significantly more time to solve the problems with 24 or more parts (problems 12 through 16) than is required for the problems with 12 or fewer parts (problems 1 through 4).

V. CONCLUSION

In this study, five heuristic procedures were presented for generating solutions to the model. These procedures were tested on 16 problems. Four of the procedures were tabu search based procedures and performed better than the CB procedure in terms of the cost of the solutions generated. The TSH2 procedure performed the best or was very close to the best on the test problems and was recommended for generating solutions to the model. Two other approaches were also performed on the 16 test problems. The first approach considered only the average demand over the planning horizon to generate a solution. This procedure performed poorly when compared to the TSH2 procedure. The second procedure considered demand variability over the planning horizon but did not allow for reassigning a part from one cell to another. This procedure performed better than the procedure that only considered the average demand but not as well as the TSH2 procedure.

VI. FUTURE SCOPE

Additional research on the problem consists of several avenues. Other approaches for generating solutions for the model can be developed. Methods for developing optimal solutions or for obtaining a lower bound on the cost of an optimal solution could be developed. These methods could then be used to evaluate the solutions generated by heuristic procedures. Other heuristic procedures could also be developed. Possibly a genetic algorithm based procedure would perform better than the tabu search procedures. Also additional procedures for quickly generating solutions as starting solutions for the search procedures could be developed and tested. The procedure developed in this research for this purpose (CB procedure) was not successful but other procedures might result in improved solutions.

Another area for possible investigation is the trend toward shorter product life cycles in many industries. The model could help evaluate how to form cells and change the composition of cells over time in the presence of shorter product life cycles.

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