Journal of Manufacturing Engineering, December 2010, Vol. 5, Issue 4, pp 293-299

DESIGN OF CELLULAR MANUFACTURING SYSTEM UNDER DYNAMIC ENVIRONMENT FOR AN AUTO-COMPONENT MANUFACTURING INDUSTRY

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ABSTRACT

Shorter product life-cycles, unpredictable demand, and customized products have forced manufacturing firms to operate more efficiently and effectively in order to adapt to changing requirements. Traditional manufacturing systems, such as job shops and flow lines, cannot handle such environments. Cellular manufacturing system (CMS), which incorporates the flexibility of job shops and the high production rate of flow lines, has been seen as a promising alternative for such cases. The classical CMS approach is under a consideration that the products mix and demand do not change over the planning horizon i.e., the production requirement is assumed to be static in nature. This paper is aimed to develop a model and a solution approach for designing cellular manufacturing systems that addresses these shortcomings by assuming dynamic production requirements in which a planning horizon can be divided into smaller periods where each period has different product mix and demand requirements. A mathematical model and an optimal solution procedure is developed simulating the exact situation of dynamic environment with routing flexibility considering all the parameters and constraints. A case study was conducted in auto-components manufacturing industry which is a batch production industry located in Ambattur Industrial Estate, Chennai. In this paper, a solution methodology of best possible cell formation using LINGO 11.0 is presented and a critical analysis is made for converting functional layout into CMS incorporating realistic constraints and integrated approach.

Keywords: *Cellular Manufacturing System, Dynamic Production Requirements, Reconfiguration, Routing Flexibility and Case Study.*

1. Introduction

1.1 About CMS

Cellular manufacturing (CM) is a hybrid system linking the advantages of both job shops (flexibility in producing a wide variety of products) and flow lines (efficient flow and high production rate). The tenet of CM is to break up a complex manufacturing facility into several groups of machines (cells), each being dedicated to the processing of a part family. Therefore, each part type is ideally produced in a single cell. Thus, material flow is simplified and the scheduling task is made much easier. As reported in the survey by Wemmerlov and Johnson [1], production planning and control procedures have been simplified with the use of CM. Obvious benefits gained from the conversion of the shop are less travel distance for parts, less space required, efficient flow of materials, higher production rate and fewer machines needed. Since similar part types are grouped, this could lead to a reduction in setup time and allow a quicker response to changing conditions. The use of general-purpose machines and equipment in CM allows machines to be changed in order to handle new product designs and product demand with little efforts in terms of cost and time. So it provides great flexibility in producing a variety of products.

1.2 About dynamic CMS

The concept of the dynamic cellular manufacturing system (DCMS) was first introduced by Rheault et al. [2]. In the traditional CMS any changes in the product demand over time is ignored from product redesign and other factors. It assumes that the product mix and part demand is constant for the entire planning horizon. The product mix refers to a set of part types to be produced at each period. In the dynamic environment, a planning horizon can be divided into smaller periods where each period has different product mix and demand requirements. Consequently, the formed cells in the current period

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may not be optimal and efficient for the next period. To overcome disadvantages of the traditional CMS, the concept of the DCMS is introduced. In DCMS, The length of the planning horizon directly depends on the natural of the product. The DCMS is related to reconfiguration of manufacturing cells including part families and machine groups at each period. Reconfiguration involves swapping the existing machines between each pair of cells, called machine relocation, adding new machines to cells including machine replication, and removing the existing machines from cells. For example, if we encounter the season products, like clothing or heater/cooler equipments, the planning horizon may consist of two six-month periods or four three-month periods [3].

2. Literature Review

Short production life cycles, high production variety, unpredictable demand, and short delivery times have led to the development of conditions in which manufacturing systems operate under a dynamic and uncertain environment. Few research works have been reported in the literature addressing the design of CMS to deal with these dynamic and stochastic production requirements. Chen [4] developed a mathematical programming model for a system reconfiguration in a dynamic cellular manufacturing environment. Song and Hitomi [5] developed a methodology to design flexible manufacturing cells. Wilhelm et al. [6] proposed a multi–period formation of the part family and machine cell (PF/MC) formation problem. Harhalakis et al. [7] presented an approach to obtain robust CMS designs with satisfactory performance over a certain range of a demand variation. Mungwatanna [8] presented a CMS model by assuming routing flexibility in dynamic and stochastic production requirements. Chen and Cao [9] proposed an integrated model for production planning (PP) in a CMS that minimizes the inter-cell material handling cost, fixed charge cost of setting up manufacturing cells, cost of holding the finished items over the planning horizon, cost of setting up the system to process different parts in different time periods, and machine operating cost. Ioannou [10] developed a comprehensive method for transforming pure functional manufacturing shops into hybrid production systems that comprise both cellular and functional areas.

Schaller [11] proposed an integer model that considers part reallocation or equipment reallocation between cells as alternative for the design of a cellular manufacturing system to handle long-term demand changes. He employed a problem specific heuristic called CB procedure and tabu search procedure to obtain the accepted solution. However parameters like inter- and intra-cell movement of parts, operational sequence, and batch size are not considered in the model. Kioon et al. [12] proposed an integrated approach to CMS design, where production planning (PP) and system reconfiguration decisions are incorporated in the presence of alternate process routings, operation sequence, duplicate machines, machine capacity and lot splitting.

This paper presents a solution methodology for the reconfigurable cell formation problem under the dynamic production requirement incorporating various production planning parameters. The description of the problem and the development of a nonlinear programming model are presented in the next section. A case study and the computational experience is presented in section 4 to illustrate the applicability of the proposed model and the solution technique. Finally conclusions are presented in section 5.

3. Mathematical Formulation

This section covers the development of a mathematical model for a CMS in a dynamic environment taking into account routing flexibility, machine flexibility, and the ability of inter-cell relocation of machines. The guiding framework adopted in this model was developed initially by Mungwatanna [8]. This model satisfies the following expectations:

i. Establishing parts family and machine groups simultaneously.
ii. Choosing a process plan for each part type with at least inter-cell material handling costs in each period by assuming the existence of several alterative process plans for each part type.
iii. Purchasing or inter-cell relocation of machines as a necessity when the production mix and/or the demand change between periods.

3.1 Assumptions

The following assumptions are made for developing the mathematical model:

i. Operating times for all part type operations on different machine types are known.
ii. Demand for each part type in each period is known.
iii. Capabilities and capacity of each machine type are known and are constant over time.
iv. Parts are moved between cells in batches. The inter-cell material handling cost per batch between cells is known and constant (independent of quantity of cells).

v. The number of cells used must be specified in advance and it remains constant over time.
vi. Bounds and quantity of machines in each cell need to be specified in advance and they remain constant over time.
vii. Each machine type can perform one or more operations (machine flexibility). Likewise, each operation can be done on one machine type with different times (routing flexibility).
viii. Inter-cell handling costs are constant for all moves regardless of the distance travelled.
ix. Backorders are not allowed. All demand must be satisfied in the given period.

3.2 Design objectives

Multiple costs are considered in the design objective in an integrated manner. All costs involved in the design of CMSs must be incorporated. However, it is not possible to consider all costs in the model due to the complexity and computational time required. In this model, costs are limited to those that are also related to dynamic and stochastic production environments through the use of routing and machine flexibility. The objective is to minimize the sum of the following costs:

1. **Machine Cost:** The investment or purchase cost per period to procure machines. This cost is calculated based on the number of machines of each type used in the CMS for a specific period.
2. **Operating Cost:** The cost of operating machines for producing parts. This cost depends on the cost of operating each machine type per hour and the number of hours required for each machine type.
3. **Inter-cell Material Handling Costs:** The cost of transferring parts between cells when parts cannot be produced completely by a machine type or in a single cell. This cost is incurred when batches of parts have to be transferred between cells. Inter-cell moves decrease the efficiency in the CMS by complicating production control and increasing material handling requirements and flow time.
4. **Machine Relocation Cost:** The cost of relocating machines from one cell to another between periods. In dynamic and stochastic production environments the best CM design for one period may not be an efficient design for subsequent periods. By rearranging the manufacturing cells the CMS can continue operating efficiently as the product mix and demand change. However, there are some drawbacks with the rearrangement of manufacturing cells. Moving machines from cell to cell requires effort and can lead to disruption of production.

3.3 System and input parameters

The input parameter values are be supplied for each period in the planning horizon. They are as follows:

1. **Product Mix:** A set of part types to be produced in the CMS in each period. The product mix varies from period to period as new parts are introduced and old parts are discontinued.
2. **Product Demand:** The quantity of each part type in the product mix to be produced in each period.
3. **Operating sequence:** An ordered list of operations that the part type must have performed.
4. **Operating Time:** Time required by a machine to perform an operation on a part type.
5. **Machine Type Capability:** The ability of a machine type to perform operations.
6. **Machine type capacity:** The amount of the time a machine of each type is available for production in each period.
7. **Available Machines:** The available machines are the set of machines that will be used to form manufacturing cells. The necessary number of each machine type is specified by the model.

3.4 Constraints

The following constraints are imposed in the model:

1. There must be sufficient machine capacity to produce the specified product mix in each period.
2. Cell size must be specified. Upper and lower bounds can be used instead of a specific number.
3. The number of cells in the system must be specified.

3.5 Mathematical formulation

Using the notations listed in section 7, the objective function and constraints, the mathematical formulation for the dynamic CMS that forms part families and machine groups simultaneously is presented as follows:

Minimize:

$$Z = \sum_{h=1}^{H} \sum_{c=1}^{C}\sum_{m=1}^{M} N_{mch}\alpha_m + \sum_{h=1}^{H} \sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{j=1}^{O_p} D_{ph} t_{jpm} x_{jpmch}\beta_m$$
$$+\frac{1}{2}\sum_{h=1}^{H} \sum_{p=1}^{P}\sum_{j=1}^{O_p-1}\sum_{c=1}^{C}\left\lceil \frac{D_{ph}}{B_p}\right\rceil \gamma \left|\sum_{m=1}^{M} x_{(j+1)pmch} - x_{jpmch}\right|$$
$$+\sum_{h=1}^{H}\sum_{c=1}^{C}\sum_{m=1}^{M}\delta_m\left(K^{+}_{mch} + K^{-}_{mch}\right) \quad (1)$$

Subject to:

$$\sum_{c=1}^{C}\sum_{m=1}^{M} a_{jpm} x_{jpmch} = 1 \qquad \forall j,p,h \qquad (2)$$

$$\sum_{p=1}^{P}\sum_{j=1}^{O_p} D_{ph} t_{jpm} x_{jpmch} \le T_m N_{mch} \qquad \forall m,c,h \qquad (3)$$

$$\sum_{m=1}^{M} N_{mch} + \sum_{m=1}^{M} K^{+}_{mch} - \sum_{m=1}^{M} K^{-}_{mch} \ge L_B \quad \forall c,h \qquad (4)$$

$$\sum_{m=1}^{M} N_{mch} + \sum_{m=1}^{M} K^{+}_{mch} - \sum_{m=1}^{M} K^{-}_{mch} \le U_B \quad \forall c,h \qquad (5)$$

$$N_{mc(h-1)} + K^{+}_{mch} - K^{-}_{mch} = N_{mch} \qquad \forall m,c,h \qquad (6)$$

$$R_{mh} \le \sum_{c=1}^{C} K^{+}_{mch} \qquad \forall m,h \qquad (7)$$

$$R_{mh} \le \sum_{c=1}^{C} K^{-}_{mch} \qquad \forall m,h \qquad (8)$$

$$Z_{jpch} \le \sum_{m=1}^{M} x_{jpmch} \qquad \forall j,p,c,h \qquad (9)$$

$$x_{jpmch}, Z_{jpch} \qquad binary$$

$$N_{mch}, K^{+}_{mch}, K^{-}_{mch}, V_{mh}, R_{mh}, D_{ph} \ge 0 \quad and \quad \text{int}\, eger$$

The objective function given in (1) is a nonlinear integer equation. It minimizes the total sum of the machine investment cost, the operating cost, the intercell material handling cost, and the machine relocation cost over the planning horizon. The first term represents the cost of all machines required in all the CMS. The machine investment cost is obtained by summing the product of the number of machines of each type and their respective costs. The second term is the cost of operating machines. It is the sum of the products of the number of hours of each machine type and their respective costs. The third is the intercell material handling cost. Total intercell material handling cost is obtained by summing the products of the number of intercell transfers for each part type and the cost of transferring a batch of each part type. The last term is the machine relocation cost. It is the sum of the products of the number of machines relocated and their respective costs. Constraint set (2) ensure that each part operation is assigned to one machine and one cell. Constraint set (3) ensures that machine capacities are not exceeded and can satisfy the demand. Constraint sets (4) and (5) specify the lower and upper bounds of cells. Constraint set (6) ensures that the number of machines in the current period is equal to the number of machines in the previous, plus the number of machines being moved in and minus the number of machines being moved out. In other words, they ensure conservation of machines over the horizon. Constraint sets (7) and (8) ensure that the number of machines relocated is equal to minimum value between the number of machines being added to cells and the number of machines being moved out of cells. Constraint (9) is used for the calculation of inter-cell material handling in the third term of the objective function.

4. Case Study and Computational Results

A case study was conducted in an auto-component manufacturing industry which is a batch production industry located in Ambattur Industrial Estate, Chennai. There were six types of machines in the industry and were arranged in job shop style, i.e. all automatic lathes (drop) in one cell, all capstan lathes in one cell, rolling, grinding, punching machines and centre lathe in one cell. Industry was facing problems in the functional layout, such as, more material movement cost, more work-in-progress and no co-ordination between different departments for minimization of scrap and rework. Conversion of the job shop layout into CMS layout will overcome the problems mentioned earlier. The conversion required extensive data collection which is tabulated below in Tables 1, 2 and 3.

Table 1: Resource Data

Machine Number	Machine Type	Purchase Cost (Rs)	Relocating Cost (Rs)	Operating Cost (Rs)	V_{mh}
1	Drop	200000	1000	0.73	4
2	Capstan	175000	1000	0.73	4
3	Rolling	650000	1500	4.8	1
4	Grinding	200000	1500	1.56	1
5	Punching	15000	200	10.5	1
6	Centre lathe	150000	300	0.7	1

Purchase cost, operating cost and relocation cost are machine specific. *Vmh* in Table 1 denotes the denomination of machines actually available in the industry. Also the availability i.e., capacity of all the machines are assumed as 7000 minutes. During period 1, six parts (1, 2, 3, 4, 5, and 6) are required to be manufactured and machine types of 1, 2, 4, 5, and 6 are required to produce them.

Table 2: Machine Types and Processing Times for Part Type Operations

Part	Operation 1		Operation 2		Operation 3	Operation 4	Operation 5
1	M1	M2	M1	M2			
	1.2	6	1.2	6			
2	M2		M2		M5	M6	
	0.5		0.6		0.3	0.3	
3	M1		M4				
	0.2		0.24				
4	M1		M1				
	2.0		1.0				
5	M1		M2				
	2.5		0.67				
6	M1		M2		M6		
	0.75		0.75		0.67		
7	M1		M1				
	1.0		1.0				
8	M2		M4				
	0.3		0.08				
9	M1		M2		M4	M3	M2
	0.5		1.0		0.1	0.1	0.3
10	M1		M3		M2	M2	
	0.5		0.08		1.0	0.3	
11	M3		M1	M2	M2		
	0.05		0.5	2.5	0.17		

Table 3: Product Mix and Demand in Each Period

Part Number	Part Demand Period 1	Part Demand Period 2
1	1000	0
2	100000	0
3	5000	0
4	5000	0
5	3000	0
6	5000	5000
7	0	3000
8	0	8000
9	0	13000
10	0	3000
11	0	5000

Table 2 presents the machine types used and the processing times in minutes for each part type operations. Part 1 requires two operations to be completed; operation 1 can be performed either in M1 having machining time 1.2 minutes or M2 having machining time 6 minutes; operation 2 can be done either in M1 having machining time 1.2 minutes or M2 having machining time 6 minutes. This provides the routing flexibility.

Table 3 presents the product mix and part demand for both periods. Period refers to the time period of weeks, months or years depending on the nature and of the product to be produced. For this auto-components manufacturing industry, the period is assumed in years. During period 1, six part types 1, 2, 3, 4, 5, 6 are needed to be manufactured and machine types of 1, 2, 4, 5, 6 are required to produce them. During period 2, six part types 6, 7, 8, 9, 10, and 11 were needed to be manufactured and machine types of 1, 2, 3, 4, 6 are required.

Numerical results from the proposed mathematical model and the optimal solution obtained using LINGO 11.0 software package are shown in Tables 4 and 5. Numbers in the parenthesis are the number of machines required for each type. '*'s represent intercell moves.

Table 4 presents optimal solution for period 1. Cell 1 consists of one machine each of types 1 and 2, and part types of 1 and 4 are produced in this cell. Cell 2 consists of one machine each of types 1, 2, 4 and 5, and part types of 2 and 3 are produced in this cell. Cell 3 consists of one machine each of types 1, 2 and 6, and part types of 5 and 6 are produced in this cell.

The total cost in period 1 includes: (i) The machine purchase cost of Rs.14, 90, 000 for nine machines. (ii) The operating cost of Rs.76, 904.30. (iii) No intercellular material handling cost. (iv) No machine relocation cost.

Table 5 presents optimal solution for period 2. Cell 1 consists of one machine each of types 1, 2, and 3, and part types of 10 and 11 are produced in this cell. Cell 2 consists of one machine each of types 1, 2, 4 and 5, and part types of 7, 8 and 9 are produced in this cell. Cell 3 consists of one machine each of types 1, 2 and 6, and part type of 6 is produced in this cell. The total cost in period 2 includes: (i) The machine purchase cost of Rs. 6,50,000 for a unit of machine type 3. (ii) The operating cost of Rs. 49,039.90. (iii) The intercellular material handling cost of Rs.2600. (iv) No machine relocation cost.

It may be noted that machine type 5 in cell 2 is no longer required for manufacturing purpose; however the machine remains in cell 2. Machine type 3

Table 4: Optimal Solution for Period 1

Cell	Machine Type (N_{mch})	Part Type 1	4	2	3	5	6
1	1 (1)		1				
	2 (1)	1					
2	1 (1)				1		
	2 (1)			1			
	4 (1)			1	1		
	5 (1)			1			
3	1 (1)					1	1
	2 (1)					1	1
	6 (1)						1

Table 5: Optimal Solution for Period 2

Cell	Machine Type (N_{mch})	Part Type 10	11	7	8	9	6
	1 (1)	1	1			*	
	2 (1)	1	1			*	
1	3 (1)	1	1				
	1 (1)			1		1	
	2 (1)				1	1	
	4 (1)				1	1	
2	5 (1)						
	1 (1)						1
	2 (1)						1
3	6 (1)						1

Table 6: Cellular Design Costs

Cost	Period 1	Period 2
Equipment	Rs. 14,90,000	Rs. 6,50,000
Operating	Rs. 76,904.30	Rs. 49,039.90
Intercellular movement	0	Rs. 2600
Relocation	0	0
Total	Rs. 15,66,904.30	Rs. 7,01,639.9

was added in first cell and no relocations were necessary. Also in period 2, part type 9 is primarily produced in cell 2, but intercell moves occur when batches of this part type are moved from cell 2 (machine 1, 2 and 4) to cell 1 (machine 2 and 3). Table 6 presents the cellular design costs for each period.

5. Conclusion

In this work, a multi-objective integrated cell formation mathematical model to deal with the design of dynamic cellular manufacturing systems for a multi-period planning has been presented. The proposed solution model considered dynamic production requirement during the design stage itself. Also simultaneous consideration of various production parameters such as alternate routing, operation sequence, duplicate machines, uncertain product mix, uncertain product demand, batch size, processing time and machine capacity, has made the cell formation more complex but more realistic. The applicability of the proposed model is illustrated with the case study carried out in the auto-components manufacturing industry. The proposed model also has the advantage of forming machine cells and part families simultaneously. Though the proposed model using LINGO can find the optimal solution for only small- and medium-sized problems, it is not suitable for large problems; because the memory and computational time requirements are extremely high, and increase exponentially, as the problem size increases. Meta heuristics like Genetic Algorithm (GA), Simulated Annealing (SA) and Tabu Search (TS) may be attempted to handle such large size NP-hard problems. Also this work can be further extended to the mutli-period design CMS under stochastic production requirements.

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Notations Used

Indices

c = index for manufacturing cells ($c=1,\dots, C$)
m = index for machine types ($m=1,\dots, M$)
p = index for part types ($p=1,\dots, P$)
j = index for operations required by part p ($j=1, O_p$)
h = index for time periods ($h=1,\dots, H$)

Input parameters

t_{jpm} = time required to perform operation j of part type p on machine type m
D_p = demand for product p
B_p= batch size for inter-cell movements of part p
α_m = amortized cost of machine of type m
β_m = operating cost per hour of machine type m
γ = intercell material handling cost per batch
δ_m = relocation cost of machine type m
T_m = capacity of each machine of type m (hours)
L_B = upper bound cell size
a_{jpm} = 1, if operation j of part type p can be done on machine type m;
0, otherwise.

Decision variables

N_{mch} = number of machines of type m used in cell c during period h

K^{+}_{mch} = number of machine type m added in cell c during period h

K^{-}_{mch} = number of machine type m removed in cell c during period h

x_{jpmch} = 1, if operation j of part type p is done on machine type m in cell c in period h;
0, otherwise.

Z_{jpch} = 1, if operation j of part type p is done in cell c in period h; 0, otherwise.

Acknowledgment

The authors acknowledge Mr. R. Velayutham for supporting us to do this case study in his industry and for freely sharing all the valuable data. The authors also acknowledge the useful comments and suggestions of the anonymous reviewers.