Investigation on Effects of Alternative Process Routing in the Design of Cellular Manufacturing System

Hemanta Singha¹, V. Jayakumar¹ and G. Ragul²

¹Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha University, Chennai, India; hemantasingha469@gmail.com, jkmails2k2@yahoo.com
²Department of Mechanical Engineering, Budge Budge Institute of Technology, Kolkata – 700137, West Bengal, India; ragulme90@gmail.com

Abstract

Background/Objectives: The adoption of cellular manufacturing becomes promising manufacturing philosophy to address the problems of today's manufacturing plants such as an increasingly turbulent environment and rising customer requirements. Method/Statistical Analysis: Group Technology and Cellular Manufacturing System (CMS) have together paved way for the same through processing of similar parts groups as part families and the formation of a machine cell dedicated for the manufacture of the part family. The traditional CMS design methods do not incorporate many real-life manufacturing parameters such as batch size and machine flexibility, various cost factors at the design stage and also they are not taking the advantage of the machine flexibility in terms of coexistence of alternate process routing. Findings: In this work, a comprehensive mathematical model has been developed capturing these exact production parameters. An optimal solution is obtained using Lingo 8.0 software package and a solution methodology of best possible cell configurations is formed. Applications/Improvements: The effect of considering the alternate process routing in the design stage of CMS is evaluated and it is found that routing flexibility results in better cell configurations.

Keywords: Alternative Routing, Cellular Manufacturing System (CMS), Operation Sequence and Varying Batch Size

1. Introduction

Cellular Manufacturing Systems (CMS) have been characterized as having the capability to react to unpredictable market changes in a cost effective manner by adjusting their capacity and functionality. The CMS 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 underlying principles, characteristics, advantages, limitations and applications of CMS can be found in the literature¹⁻³.

Many researchers have extensively studied and developed the classical CMS (CCMS) design methods which considered static and deterministic production requirements. Extensive reviews of classical CF can be obtained from references⁴⁻¹¹. Binary machine-part incidence matrix and/or limited subset of production parameters were most of the suggested models¹². However effective CMS design requires the use of many manufacturing information such as alternate routing, demand, processing duration and cost, movement of parts between and within cells, machine capacity, machine maintenance and overhead cost, varying batch size, availability of machines and material handling capacity¹².

The alternative process routing is either overlooked or ignored completely in most of the CMS literature. It is evidenced that when alternative routes are considered at the design stage it would result in improved cell configurations with reduced total system cost. Therefore, a
comprehensive mathematical model which encompasses several real-life production requirements such as operation sequence, duplicate machines, batch size, product demand, operation time, machine flexibility, routing flexibility and various cost factors would need to be developed.

2. Problem Development and Model Development

In this work, a comprehensive mathematical model has been developed capturing the exact production parameters. The guiding framework adopted in this model was developed in 14,15.

3. Assumptions Made

1. Each part type’s processing time and demand are known and deterministic
2. The inter-cell and intra-cell batch sizes and the associated costs are known and constant.
3. The cell size i.e. quantity of machines in a cell and the number of cells assigned should be specified in advance and they remain constant over time.

3.1 Notations Used

3.1.1 Indices

The notations used in the model 16 are presented below:

$c$ = machine cells’ index ($c = 1,..., C$)

$m$ = machine types’ index ($m = 1,..., M$)

$p$ = part types’ index ($p = 1,..., P$)

$j$ = part type’s operations index ($j = 1,..., O_p$)

3.1.2 Input Parameters

$P$ = number of part types

$O_p$ = number of operations for part type $p$

$M$ = number of machine types

$C$ = maximum number of cells that can be formed

$D_p$ = demand for part type $p$

$t_{jpm}$ = time required for processing operation $j$ of part type $p$ on machine type $m$.

$a_{jpm} = 1$, if operation $j$ of part type $p$ can be done on machine type $m$; 0 otherwise

$B_{\text{inter}}$ = batch size for inter-cell movements of part type $p$

$B_{\text{intra}}$ = batch size for intra-cell movements of part type $p$

$\gamma_{\text{inter}}$ = inter-cell material handling cost per batch of part type $p$

$\gamma_{\text{intra}}$ = intra-cell material handling cost per batch of part type $p$

$a_m$ = constant cost of machine of type $m$

$\beta_m$ = operating cost of machine type $m$ for each hour.

$T_m$ = time capacity of machine $m$ in hours

$UB$ = maximal cell size

3.1.3 Decision Variables

$N_{mc} = \text{number of machines of type } m \text{ assigned to cell } c$

$x_{jppmc} = 1$, if operation $j$ of part type $p$ is one on machine type $m$ in cell $c$; 0 otherwise

3.1.4 Mathematical Formulation

The nonlinear mathematical model to simultaneously form part families and machine cells is given below:

Minimize:

$$Z = \sum_{c=1}^{C} \sum_{m=1}^{M} N_{mc} a_m + \sum_{p=1}^{P} \sum_{j=1}^{O_p} \sum_{m=1}^{M} \beta_m t_{jpm} x_{jpmc}$$

$$+ \sum_{p=1}^{P} \sum_{j=1}^{O_p-1} \sum_{m=1}^{M} \frac{D_p}{\gamma_{\text{inter}}} \times \left( \left| \sum_{m=1}^{M} x_{j(pm+1)c} - \sum_{m=1}^{M} x_{jpmc} \right| \right)$$

$$+ \sum_{p=1}^{P} \sum_{j=1}^{O_p-1} \sum_{m=1}^{M} \frac{D_p}{\gamma_{\text{intra}}} \times \left( \left| \sum_{m=1}^{M} x_{j(pm+1)c} - \sum_{m=1}^{M} x_{jpc} \right| \right)$$

Subject to

$$\sum_{c=1}^{C} \sum_{m=1}^{M} a_{jpm} x_{jpmc} = 1 \quad \forall j, p$$

$$\sum_{p=1}^{P} \sum_{m=1}^{M} D_p t_{jpm} x_{jpmc} \leq T_m N_{mc} \quad \forall m, c$$

$$\sum_{m=1}^{M} N_{mc} \leq UB \quad \forall c$$

$$x_{jpmc} \in \{0, 1\}, N_{mc} \geq 0 \text{ and integer}$$
3.1.5 Objective Function and Model Constraints

The objective function given in (1) minimizes (i) cost of machine maintenance and overheads, (ii) operating cost of machines, (iii) cost of inter-cell material handling cost and (iv) cost of intra-cell material handling.

The assignment of each part operation to one machine and one cell is represented in constraint (2). The requirement of meeting the demand and not exceeding the machine capacities are represented in constraint (3). The maximum cell size requirement is ensured in constraint set (4). Constraint (5) ensures that quantity of machines assigned to cell should not be zero and operation of a part assigned to a machine in a cell is indicated at 1; 0 otherwise.

4. Optimal Solution Procedure

The proposed model is implemented in Lingo 8.0 optimal software package and the experiments have been run on a Intel Core i5 @ 2.2 GHz Personal Computer with 4 GB RAM.

4.1 Illustrative Example

In this section, a problem set of $8 \times 6$ (8 parts and 6 machines) derived from the published data in the CMS design literature is used. The input parameters are shown in Table 1.

Table 2 shows the data types such as the batch size for production, inter-cell and intra-cell movements and the demand for the parts.

Table 3 shows the aspects of machine type such as the constant cost, the operating cost per hour and the time capacity of each machine.

### Table 1. Input parameters used

| Parameter                          | Value |
|------------------------------------|-------|
| Number of part types, $P$          | 8     |
| Number of machine types, $M$       | 6     |
| Maximum number of cells that can be formed, $C$ | 3     |
| Maximum cell size, $U_B$           | 5     |
| Number of alternative machines for processing operation $j$ of part $p$ | 2     |
| Maximum number of operations of a part | 5     |
| Inter-cell material handling cost per batch, $g_{inter}$ | $50$  |
| Intra-cell material handling cost per batch, $g_{intra}$ | $5$   |

### Table 2. Data for part types

| Part type, $p$ | Production batch size, $B_{prod}^p$ | Inter-cell batch size, $B_{inter}^p$ | Intra-cell batch size, $B_{intra}^p$ | Demand, $D_p$ |
|----------------|-------------------------------------|-------------------------------------|-------------------------------------|---------------|
| P1             | 100                                 | 100                                 | 20                                  | 1500          |
| P2             | 125                                 | 125                                 | 25                                  | 2650          |
| P3             | 125                                 | 125                                 | 25                                  | 2350          |
| P4             | 125                                 | 125                                 | 25                                  | 2600          |
| P5             | 75                                  | 75                                  | 15                                  | 1350          |
| P6             | 50                                  | 50                                  | 10                                  | 1850          |
| P7             | 50                                  | 50                                  | 10                                  | 2100          |
| P8             | 125                                 | 125                                 | 25                                  | 1700          |

### Table 3. Data for machine types

| Machine type, $m$ | Maintenance and overhead cost ($) | Operating cost per hour ($) | Capacity (hours), $T_m$ |
|-------------------|-----------------------------------|-----------------------------|------------------------|
| M1                | 450                               | 7                           | 2000                   |
| M2                | 700                               | 12                          | 2000                   |
| M3                | 500                               | 6                           | 2000                   |
| M4                | 600                               | 9                           | 2000                   |
| M5                | 500                               | 11                          | 2000                   |
| M6                | 600                               | 12                          | 2000                   |

### Table 4. Machine-part operation

| Part type, $p$ | (Machine, Processing time) | Operation 1 | Operation 2 | Operation 3 | Operation 4 | Operation 5 |
|----------------|---------------------------|-------------|-------------|-------------|-------------|-------------|
| P1             | (M2, 27)                  | (M1, 27)    | (M1, 18)    | (M4, 37)    | (M1, 25)    |
| P2             | (M1, 30)                  | (M2, 36)    | (M3, 24)    | (M4, 34)    | (M2, 15)    |
| P3             | (M1, 18)                  | (M3, 40)    | (M3, 30)    | (M3, 26)    | (M3, 39)    | (M6, 32)    |
| P4             | (M2, 24)                  | (M3, 30)    | (M2, 24)    | (M4, 29)    |             |             |
| P5             | (M5, 82)                  | (M2, 23)    | (M1, 24)    | (M4, 29)    | (M4, 25)    |             |
| P6             | (M1, 19)                  | (M5, 27)    | (M3, 35)    | (M1, 25)    | (M1, 25)    | (M5, 29)    |
| P7             | (M3, 20)                  | (M1, 36)    | (M5, 24)    | (M3, 18)    | (M2, 30)    | (M6, 22)    |
| P8             | (M5, 18)                  | (M1, 32)    | (M2, 26)    | (M2, 26)    |             |             |
Table 5. Cell configuration for the described problem

| Cell | Machine Types | Quantity | PF1 | PF2 | PF3 |
|------|---------------|----------|-----|-----|-----|
| 1    | M1            | 1        | 3,5 | 1   | 2   |
|      | M3            | 2        | 3,4,5 | 2   | 3,5 |
|      | M4            | 1        | 4   | 3,5 | 2   |
| 2    | M1            | 1        | 1   | 1   | 15,4 |
|      | M5            | 1        | 4   | 2   | 2   |
|      | M6            | 1        | 3   | 3   | 3   |
|      | M3            | 1        | 2   | 4   | 3   |
| 3    | M5            | 1        | 1   | 1   | 1   |
|      | M2            | 1        | 2   | 4   | 3   |
|      | M3            | 1        | 2   | 4   | 3   |
|      | M4            | 1        | 2   | 4   | 3   |

Table 4 presents machine-part operation data related to number of operations, processing times and alternate process routings. Operations of each part are assigned to the machine depending on its availability and alternate machines are also assigned for operations which can be processed otherwise. For instance, operation 1 of Part 1 can be done either on M2 or M5 whereas operation 5 can be done only on machine M1.

In Table 5, the matrix elements inside the shaded region are grouped as part family and the elements responsible for inter-cell movements are outside the shaded region. For instance, P8 requires one inter-cell movement (between cells C2 to C1) and one intra-cell movement within Cell 1 (between M1 and M4).

For the proposed linearized mathematical model have 2254 variables and 606 constraints. The best solution obtained for the problem instance is presented in Table 6.

5. Evaluation of Potential Benefits of Incorporating Alternative Process Routing

The presence of alternative routings improves the chances of many ways of forming possible manufacturing cells. In most CMS literature, pre-specified routes are employed and availability of alternate routes is overlooked. Most works considered only one process routing for each part without considering the coexistence of alternative routes. In our model, the coexistence of alternate routing is considered at the design stage. The coexistence of alternative routing can be prevented by assigning a single process route for each part so that each operation can have exactly one route which can be processed on one machine type.

Table 6. Best cellular design costs for adaptive design

| Cost                      | Value ($) |
|---------------------------|-----------|
| Machine constant cost     | 6400.00   |
| Machine operating cost    | 151915.00 |
| Inter-cell material handling cost | 3390.00 |
| Intra-cell material handling cost | 11910.00 |
| Best objective value function cost | 173615.00 |

State: Global Optimal Solution
Run time: 3 hours: 22 minutes: 02 seconds

Table 7. Potential benefits of incorporating alternative process routing

| Problem Number | Problem Information | OFV without considering Alternative routing ($) | OFV considering Alternative Routing ($) | Progress |
|----------------|---------------------|-----------------------------------------------|----------------------------------------|----------|
| P M O          | OFV without        | OFV considering                              |                                        |          |
| 1              | 8 6 5               | 204720.5                                     | 173615.0                               | 31105.5 (15.91%) |
| 2              | 9 5 3               | 282653.5                                     | 224035.0                               | 58618.5 (20.73%) |
| 3              | 10 7 3              | 276293.3                                     | 268954.7                               | 43148.0 (15.95%) |
| 4              | 11 6 3              | 268954.7                                     | 225195.0                               | 43759.7 (16.27%) |

Table 7 depicts the comparison of solutions obtained considering with or without alternative routings. The consideration of alternative routing in cellular manufacturing system shows that there is significant amount of reduction in the overall cost. As a result of alternative routing, the costs of inter-cell and intra-cell movements, operation cost, and machine constant cost are reduced significantly. This is because the presence of alternative routings improves the chances of many ways of forming possible manufacturing cells. Thus, routing flexibility results in better configurations than the configuration with a single route.

6. Conclusion

In this work, an integer mathematical model has been developed capturing the exact production parameters such as operation sequence, duplicate machines, batch size, product demand, operation time, machine flexibility, routing flexibility and various cost factors. The consideration of these real-time manufacturing issues resulted in more realistic and effective cell formation model. An optimal
solution is obtained for the developed model using Lingo 8.0 software package and a solution methodology of best possible cell configurations is formed. The results obtained suggest that considering alternate process routing at the design stage would reduce the overall cost up to a significant margin. This work can be further extended to the design of CMS under dynamic and stochastic production requirements.

7. References

1. Kusiak A. The generalized group technology concept. International Journal of Production Research. 1987 Jan; 25(4):561–69.
2. Jayakumar V, Raju R. An adaptive cellular manufacturing system design with routing flexibility and dynamic system reconfiguration. European Journal of Scientific Research. 2010; 47(4):595–611.
3. Singh N. Design of Cellular Manufacturing Systems. European Journal of Operational Research. 1993 Sep; 69(3):284–91.
4. Heragu SS, Gupta YP. A Heuristic for designing cellular manufacturing facilities. International Journal of Production Research. 1994; 32(1):125–40.
5. Felix Offodile, Abraham Mehrez, John Grznr. Cellular Manufacturing: A taxonomic review framework. Journal of Manufacturing Systems. 1994 Dec; 13(3):196–220.
6. Shargal M, Shekhar S, Irani SA. Evaluation of search algorithms and clustering efficiency measures for machine-part matrix clustering. IIE Transactions. 1995; 27(1):43–59.
7. Joines J, Culbrett C, King R. A comprehensive review of production oriented cell formation techniques. International Journal of Factory Automation and Information Management. 1996 Aug; 3(4):225–65.
8. Cheng, Kumar A, Motwani JG, Reisman A, Madan MS. Cellular Manufacturing: a statistical review of the literature. Operations Research. 1997 Jul-Aug; 45(4):508–35.
9. Hassan M Selim, Ronald G Askin, Asoo J Vakharia. Cell formation in group technology: review, evaluation and directions for future research. Computers and Industrial Engineering. 1998 Jan; 34(1):3–20.
10. Sarkar, Mondal. Grouping efficiency measures in cellular manufacturing: a survey and critical review. International Journal of Production Research. 1999 Jan; 37(2):285–314.
11. Mansouri SA, Moattar-Hussein SM, Newman ST. A review of the modern approaches to multi-criteria cell design. International Journal of Production Research. 2000 Nov; 38(5):1201–18.
12. Defersha FM, Chen M. A parallel genetic algorithm for dynamic cell formation in cellular manufacturing systems. International journal of Production Research. 2008 Oct; 46(22):6389–413.
13. Husamettin Bayram, Ramazan Sahin. A comprehensive mathematical model for dynamic cellular manufacturing system design and Linear Programming embedded hybrid solution techniques. Computers and Industrial Engineering. 2016 Jan; 91(C):10–29.
14. Anan Mungwatanna. Design of cellular manufacturing systems for dynamic and uncertain production requirement with presence of routing flexibility. Dissertation, Blacksburg State University Virginia, 2000 Sep.
15. Tavakkoli-Moghaddam R, Aryanezhad MB, Safaei N, Azaron A. Solving a dynamic cell formation problem using meta-heuristics. Applied Mathematics and Computation. 2005 Nov; 170(2):761–80.
16. Jayakumar V, Raju R. A simulated annealing algorithm for machine cell formation under uncertain production requirements. Arabian Journal of Science and Engineering. 2014; 39:7345–54.