Design Of Virtual Manufacturing Cells: An Integrated Approach

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Cellular Manufacturing (CM) is being used as a philosophy with broad applicability in manufacturing sector. But existing approaches to cell formation forces each part of a part family to belong to only one machine cell. In order to attain mutual separability in machine part cluster, machines of a particular manufacturing cell operate upon parts of only the corresponding class. However, forcing parts into families or duplicating machines without any economic considerations might be counter productive to the essence of group technology and might even result in more cost than intercellular material movement or subcontracting. These approaches fail to merge part families with overlapping machine requirements. This paper presents a four-phase approach for cell formation, which integrates machine grouping and layout design, neglecting part family formation. The proposed approach uses hybrid layouts that seek to preserve the part family and cellular focus of the original set of cells designed to replace existing functional layout in a job shop. The approach is illustrated with an example.

Keywords: Cellular manufacturing, cell formation, hybrid layout, virtual manufacturing cells.

1. Introduction

During the past decade, there has been a major shift in the design of manufacturing planning and control systems using innovative concepts such as just-in-time (JIT) production, flexible manufacturing systems (FMS) and cellular manufacturing (CM). CM in particular has received considerable interest from both practitioners and academicians because it allows small, batch-type, production to gain an economic advantage similar to that of mass production and still retaining the high degree of flexibility associated with the job-shop production.

A number of case studies (Gupta and Tompkins, 1982; Hyer and Wemmerlov, 1982) report that significant improvements can be achieved in areas such as lead times, set-up times, work-in-process, quality, machine utilisation and employee job satisfaction. A survey conducted on the impact of CM on Australian industries with over $10 million annual turnover showed that about 209 companies (accounting for 52% of the companies surveyed) are already using or are in process of implementing CM, with a further 28% indicating their future plans to introduce CM to some parts of their operations. Of the companies already using CM, more than 70% reported improvements in one or more aspects of lead times, lot sizes, labour productivity, set-up times, on-time delivery, labour flexibility and quality (Kaebernick and Bazargan-Lari, 1996).

For the majority of the time (about 95% of the total time spent on the shop), the material, which is under production, does not undergo any value addition (Lee and Chen, 1997; Shanker and Vrat, 1998). Therefore, organisation, design, planning and control of production system are very significant areas for achieving

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improvements. For this purpose, the principles of CM can be implemented by scheduling a functionally organised shop using rules that recognise the existence of part families. In such a case the machines can be temporarily dedicated to a family rather than individual part.

The traditional definition of a manufacturing cell is somewhat restrictive (Henry and Abdelaziz, 1988). The requirements that each cell functions as a modified flow shop, and the parts within the family must go from raw material to finished parts, within a single cell, makes the manufacturing cells configuration problem very complex. This is in fact an illusion in a typical industrial application, which will lead to a large number of machines being assigned to the remainder cell (a job shop). The presence of alternate process plans, duplication of machines, and subcontracting may not always eliminate the problem of 'inter-cell' flows. Hence, there is a need to relax the restriction by allowing parts to move between cells. Virtual cells allow the time sharing of machines among different cells producing different part families, but having overlapping resource requirement (Irani et al., 1993). Thus the restriction of confining a part to only one cell is relaxed. Moreover, virtual cell defines a grouping of machines only in the system control software. So machines retained in a functional layout can be dedicated to parts from a family without physically disturbing those shared machines among two or more cells. Simply by assigning different tools and fixtures to a machine, it can be assigned to different part families in successive production periods.

This paper presents a new approach for the formation of virtual cells. The proposed method is a flow based approach for the formation of virtual manufacturing cells that integrates the machine grouping, shop layout design and inter-cell flow handling. The proposed methodology is capable of generating multiple cell design solutions.

The rest of the paper is organized as follows. A brief literature review on cellular manufacturing research is presented in section 2. In section 3, an integrated approach for formation of virtual cells is presented. Through an illustrative example, the capability of the integrated approach in generating multiple cell design solutions is presented in section 4. This is followed by the concluding remarks in the last section.

2. Literature Review

Shafer and Rogers (1991) proposed goal programming model combined with the p-median (for identifying part families) and travelling salesman problem (to determine the optimal sequence of parts). The criteria considered by the authors include minimising set-up times (through parts sequencing), minimising intercellular movements, minimising the investment in new equipment, and maintaining an acceptable machine utilisation level. The author applies goal programming to three unique situations: setting up an entirely new system and purchasing all new equipment, reorganising the system using only existing equipment, and reorganising the system using existing and some new equipment.

Venugopal and Narendran (1992) proposed a bi-criteria mathematical model for the machine-part grouping problem. The authors consider two minimisation objectives: minimise the volume of inter-cell moves, and minimise the total within cell load variation.

Akturk and Balkose (1996) calculate the similarity and dissimilarity of parts for cell formation. The authors make use of the objectives such as minimising: the dissimilarity of parts based on the design and manufacturing attributes, the dissimilarities based on the operation sequences, the total machine investment cost, the sum of the workload variability in each cell, the workload variability in different cells, and the number of skipping which refers to the number of machines a part skips in its operation sequence. The authors suggest a multi-objective cluster analysis to deal with these objectives simultaneously.

Lee and Chen (1997) developed a weighted three-phase approach, which not only forms machine cells and part families, but also allows machine duplication wherever necessary. Phase 1 determines the workload balances for duplicated machines. Phase 2 constructs machine cells and part families by employing heuristic algorithm. Phase 3 improves the solution quality using heuristics. The two criteria considered are: minimising inter-cell movement of parts and maximising workload balance among duplicated machines.

Su and Hsu (1998) consider three objectives in their model. The objectives are: minimising the total cost of inter-cell transportation, intra-cell transportation and machine investment; minimising intra-cell machine (in cell) load unbalance; and minimising inter-cell machine (in plant) load unbalance. The authors unified these objectives through weighting and solved the model by means of parallel simulated annealing.

In the pioneering work of Hollier (1963), Carrie (1975), and Carrie and Mannion (1976) on unidirectional flow line design, the flows in the travel chart and operation sequences used as input data have been classified as (a) in-sequence, (b) bypass or (c) backtrack. This classification is sufficient since they considered the optimum layout of a single group of machines only, thus encouraging duplication among cells. However if inter-cell layout must be incorporated with intra-cell layout, an additional type of flow is created as the cells have common machine requirements. Such types of inter-cell flows are known as cross flows. This type of flow reduces number of machines available within a cell for duplication. But they pose problems like higher queuing delays for parts involved and machine utilisation. However, with the advances in handling system capabilities, the intra-cell machine duplication problem can be considered secondary to that of inter-cell flows (Irani et al., 1993).

The design of a CM system is quite challenging because so many strategic issues, e.g. the selection of parts suitable for manufacturing on a group of machines, the level of machine flexibility, the layout of cells, the types of material handling equipment, and the types and numbers of tools and fixtures, must be considered during design. Several techniques have been introduced to solve the cellular manufacturing problem. Most of these techniques are presented in the Literature review. The approaches found in the literature fail to address the following issues properly:

(1) Feasibility of non-independent cells having inter-cell flows and machine sharing among them.
(2) Concentration on machine grouping and part family and neglecting flow directions and flow volumes.
(3) Impact of layout of cells and layout of machines within a cell.
(4) Effect of sequence of operations on material handling costs and times.

Hence there is need to develop an algorithm which addresses the above mentioned issues. Our approach is a flow based approach for the formation of virtual manufacturing cells which integrates machine grouping, shop layout design and inter-cell flow handling.

3. Integrated approach for formation of virtual cells

The concept of a virtual manufacturing cell has been proposed by the National Bureau of Standards to address specific control problems in the design of their Automated Manufacturing Research Facility (Simpson et al., 1982). Virtual cells are dynamically formed cells in which machines are configured logically and temporarily. These cells are defined only in the system control software, which provide an added flexibility to the system. It allows time sharing of machines with other cells by virtue of overlapping resource requirements. This is referred to as virtual cellular manufacturing (VCM). The VCM production control scheme creates the illusion of production using manufacturing cells without physically changing a process layout, yet still achieves the benefits of cellular manufacturing

(Kannan and Ghosh, 1996).

Several researchers (Ang and Willey, 1984; Flynn and Jacobs, 1987; Gupta and Tompkins, 1982) have investigated the utility of a hybrid layout for batch manufacturing by using simulation. Hybrid layout is a combination of functional and cellular layouts that is similar to the concept of virtual cells. These layouts relaxes the traditional view that a cell must be dedicated to a part family and represent a novel fusion of partial conversion to a cellular layout, functional grouping of several shared machine types, limited physical duplication of shared machines and inter-cell flows.

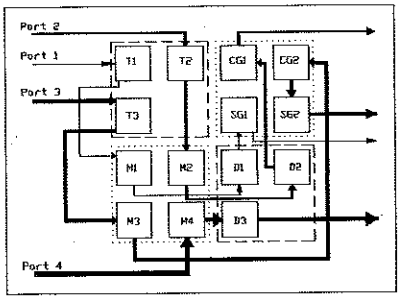

Figure 1(a): *Functional layout (Gallagher and Knight, 1973)*

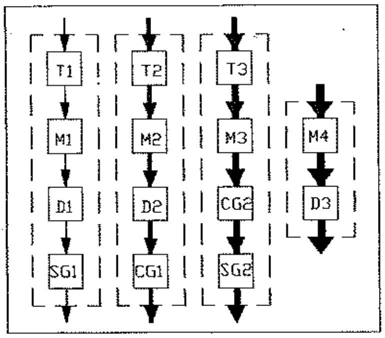

Figure 1(b): *Cellular layout (Gallagher and Knight, 1973)*

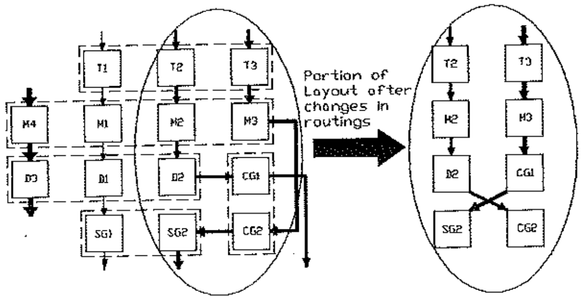

Figure 1(c): *Hybrid layout (Gallagher and Knight, 1973)*

Figure 1(a) is the standard representation for a functional layout, which when reorganised on a part family basis into cells, appears as in Figure 1(b). Figure 1(c) demonstrates the concept of hybrid layout that combines the properties of the functional layout of Figure 1(a) and the cellular layout of Figure 1(b). The flow lines in the Figure 1(b) have been permuted in order to bring the identical machines next to each other without destroying the allocations of the machines to particular part families. However, they are retained in functional layouts to allow flexibility in machine reassignments when machines breakdown or the part mix and/or demand volumes change. Virtual cells allow those flow lines that use the same sequence of machines to be merged. These cells also create functional sections for the shared machines. This will result in a hybrid layout of functional sections and machine groups only for those machines that are specific to a single part family.

Hybrid layouts are realised by modifying (a) the machine-part compositions of the cell or (b) the shapes of the cells or (c) the orientations of the cells or (d) the locations of the cells (Huang and Irani, 1999). Hybrid layout allows use of a very limited amount of input data. Using machine-specific data, such as the flow network captured in a travel chart, which aggregates the operation sequences and batch quantities, can solve the related problems of designing intra-cell and inter-cell layouts. Suitable aisle capabilities are assumed, which would allow random flows to some extent.

Our method is a flow based approach for the formation of virtual manufacturing cells which integrates machine grouping, shop layout design and inter-cell flow handling. Flows are measured quantitatively in terms of number of trips made by the parts between any two successive operations. Part families with overlapping machine requirements are assumed to be merged to eliminate the need to duplicate shared machines among competing cells. Proposed approach consists of four phases:

Phase 1:

Formation of primary cells by dividing operations in to three ranges (high, medium and low) by employing frequency of flow occurring between operations as a measure.

Phase 2:

Redesigning of primary cells for minimisation of number of inter-cell travels.

Phase 3:

Decomposition of individual primary cells into sub-cells by employing phase 1 and 2 again on individual primary cells.

Phase 4:

Forced decomposition of sub-cells by shifting excess machines to other cells in order to obtain multiple cell design solutions keeping in view minimisation of inter-cell flows.

4. Illustrative Example

In order to show the capability of the integrated approach in generating multiple cell design solutions, an example is introduced and solved using the integrated flow based approach described above.

The proposed method will be explained by using an example obtained from the literature (Huang and Irani, 1999). The problem concerns a system having 12 machines and 19 parts. The information regarding the part routing is given in the Table 1.

Table 1: *Operation sequences for the system of parts*

Part Number	Operation sequence
1	1,4,8,9
2	1,4,7,4,8,7
3	1,2,4,7,8,9
4	1,4,7,9
5	1,6,10,7,9
6	6,10,7,8,9
7	6,4,8,9
8	3,5,2,6,4,8,9
9	3,5,6,4,8,9
10	4,7,4,8
11	6
12	11,7,12
13	11,12
14	11,7,10
15	1,7,11,10,11,12
16	1,7,11,10,11,12
17	11,7,12
18	6,7,10
19	12

Phase 1:

Formation of primary cells by dividing flow into three ranges. Table 2 presents the actual flow that is occurring between various machines in the manufacturing system prepared by using the part routings given in the Table 1 (Huang and Irani, 1999). Table 3 presents the flows by summing of similar flows under one machine head, which is prepared by using the Table 2. This step converts the frequency matrix into a lower triangular matrix and helps in division of flows into three ranges by giving a measure of flow distribution within the cells. The maximum frequency as obtained from Table 3 is 6. So dividing the maximum frequency in three parts based on GT philosophy, the primary cells obtained are shown in Table 4.

Table 2: *Frequency chart for all machines*

	1	2	3	4	5	6	7	8	9	10	11	12
1	-	1	-	3	-	1	2	-	-	-	-	-
2	-	-	-	1	-	1	-	-	-	-	-	-
3	-	-	-	-	2	-	-	-	-	-	-	-
4	-	-	-	-	-	-	4	6	-	-	-	-
5	-	1	-	-	-	1	-	-	-	-	-	-
6	-	-	-	3	-	-	1	-	-	2	-	-
7	-	-	-	2	-	-	-	2	2	2	2	2
8	-	-	-	-	-	-	1	-	6	-	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	2	-	-	-	2	-
11	-	-	-	-	-	-	3	-	-	2	-	3
12	-	-	-	-	-	-	-	-	-	-	-	-

Table 3: *Summation frequency chart for all machines*

	1	2	3	4	5	6	7	8	9	10	11	12
1	-	-	-	-	-	-	-	-	-	-	-	-
2	1	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	3	1	-	-	-	-	-	-	-	-	-	-
5	-	1	2	-	-	-	-	-	-	-	-	-
6	1	1	-	3	1	-	-	-	-	-	-	-
7	2	-	-	6	-	1	-	-	-	-	-	-
8	-	-	-	6	-	-	3	-	-	-	-	-
9	-	-	-	-	-	-	2	6	-	-	-	-
10	-	-	-	-	-	2	4	-	-	-	-	-
11	-	-	-	-	-	-	5	-	-	4	-	-
12	-	-	-	-	-	-	2	-	-	-	3	-

Table 4: *Primary cells obtained by dividing in to three equal ranges*

Cells	Operations assigned to each cell
Low frequency cells	2, 3, 5
Medium frequency cells	1, 6 , 10
High frequency cells	4, 7, 8 , 9, 11, 12

Phase 2:

Redesign the primary cells to minimise the inter-cell travels. The primary cells obtained after redesigning might have some operations which may be contributing more to inter-cell flows as compared to intra-cell flows. So these types of machines need to be relocated to proper cells to minimise the inter-cell travels. Also operations allocated to the cells need to be re-adjusted among themselves to minimise the inter-cell travel distances. Table 5 shows the primitive cells obtained after redesigning the primitive cells to minimise the inter-cell travels.

Table 5: *Primary cells obtained after redesigning the primary cells*

Cells	Operations assigned to each cell
Low frequency cells	2, 3, 5
Medium frequency cells	1, 6, 10
High frequency cells	4, 9, 8, 7, 11, 12

Phase 3:

Decomposition of individual primary cells into sub-cells by employing phase 1 and 2 again on individual primary cells. Table 6 shows different summation frequency cells formed for individual cells formed during phase 1. However further decomposition of cells by using Table 6 lead to increase in inter-cell travels obtained. Hence the cells rearrange themselves back into original form as shown in Table 5.

Table 6: *Summation frequency chart for individual cells formed in Phase 1 (a) Low Frequency Cells, (b) Medium Frequency Cells, and (c) High Frequency Cells*

	2	3	5
2	-	-	-
3	-	-	-
5	1	2	-

	1	6	10
1	-	-	-
6	1	-	-
10	1	2	-

	4	7	8	9	11	12
4	-	-	-	-	-	-
7	1	-	-	-	-	-
8	-	-	-	-	-	-
9	3	1	-	-	-	-
11	-	1	2	-	-	-
12	1	1	-	3	1	-

Phase 4:

Forced decomposition of decomposed cells by shifting excess machines to vacant positions in other cells to obtain multiple cell design solutions. The solution generated by integrated approach for various cell numbers is shown below.

Table 7: *Final cells obtained after forced decomposition of primary cells*

Maximum number of operations that can be accommodated in a cell	Cell number	Operations assigned to cell
4	1	3, 5, 9, 12
	2	2, 1, 6, 10
	3	4, 8, 7, 11
5	1	3, 5
	2	2, 1, 6, 10, 12
	3	4, 9, 8, 7, 11
6	1	3, 5
	2	2, 1, 6, 10
	3	4, 9, 8, 7, 11, 12

Based on the multiple cell designs obtained in Table 6, the actual network representation for various cell designs are shown in Figures 2, 3 and 4 respectively. In figure 2, the maximum number of machines that can be accommodated in a cell cannot exceed 6. Similarly in figures 3 and 4, the maximum number of machines that can be accommodated in a cell cannot exceed 5 and 4 respectively. The numbers written inside cells represents the different operations, which are performed on various parts produced by the manufacturing system. The flow lines and cross arcs shown in the figures indirectly suggest the direction of flows occurring between operations, aisles for material handling and the network of automated guided vehicle (AGV) tracks. For example, the routing of part 10 in Cell 3 contains a flow path from 4 to 7 and back in the same route. Then the part goes from 4 to 8 as shown in the figure along the flow line.

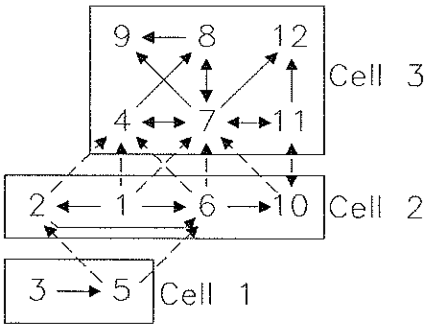

Figure 2: *Network representation of facility layout for maximum number of machines in a cell to be 6*

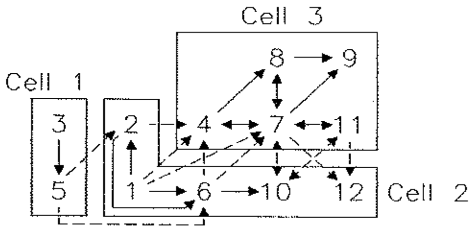

Figure 3: *Network representation of facility layout for maximum number machines in a cell to be 5*

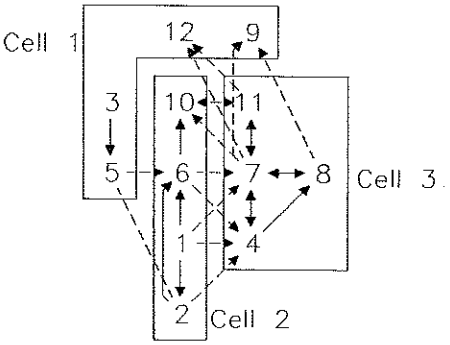

Figure 4: *Network representation of facility layout for maximum number machines in a cell to be 4*

The results obtained from our approach and those obtained in original literature are given below:

Table 7: *Final cells obtained after forced decomposition of primary cells*

Maximum number of operations that can be accommodated in a cell	Cell number	Operations assigned to cell
4	1	3, 5, 9, 12
	2	2, 1, 6, 10
	3	4, 8, 7 , 11
5	1	3, 5
	2	2, 1, 6, 10, 12
	3	4, 9, 8, 7, 11
6	1	3, 5
	2	2, 1, 6, 10
	3	4, 9, 8, 7, 11, 12

It is clear from the table that inter-cell flows increased from 7 to 13, whereas the intra-cell flows dropped from 23 to 9 and number of duplicated machines are 0 as compared to 5 in the literature. Also the method in the literature fails to produce only one design whereas the new integrated approach is able to generate three alternative solutions. So by employing virtual cells there may be a slight increase in number of inter-cell flows, but the savings in terms of duplicated machines compensates for losses due to flows. Flexibility is an added advantage provided by these cells to the system.

Advantages of the proposed method:

(1) This method is extremely useful when the system has large number of operation. The method quickly separate outs the operations.

(2) Time for convergence of the method is faster.

(3) Provides the decision maker with multiple cell designs according to maximum number of machines in a cell. It offers the flexibility to assess each alternative against tangible and intangible benefits and criteria.

Limitations of the proposed method:

The performance of the method is dependent on the phase 1. A poor division criteria can lead to a two cell combination having a large number of operations. This will in turn increase the computational effort and time for convergence will be increased drastically.

5. Concluding Remarks

CM is a major innovation in the design of production systems. But the restrictive nature of traditional definition of manufacturing cell makes it almost impossible to achieve higher efficiencies from the CM system. A new technique for formation of cells is by employing virtual cells in CM. Virtual cells relax the restrictions on cells and achieve benefits of CM by dedicating machines to families on a temporary rather than a permanent basis. Thus allowing cells to respond to changes in prevailing shop conditions. Although some efficiency is sacrificed in some areas like material handling, production control etc., but the added flexibility of VCM is more than offset for these losses. As a result of this flexibility, shop provides balanced utilisation of machines and faster response to short-term fluctuations in demand. Also this flexibility provides a premium competitive value in the current production environment, which is characterised by ever changing demands.

This paper presents an integrated four phase approach for formation of virtual cells. The approach generates machines groups, identifies flow line layout for each group and minimises inter-cell distances and travels. An approximate configuration of the aisles, conveyers or AGVS grid can be also be identified from the flow arcs. It is advisable to minimise or eliminate intra-cell and inter-cell travel distances. In this approach, the decision maker is provided with multiple cell designs according to maximum number of machines in a cell. It offers the flexibility to assess each alternative against tangible and intangible benefits and criteria. The capability of the model was demonstrated by applying it to an illustrative example.

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