MULTI-PERIOD PLANNING AND UNCERTAINTY ISSUES IN CELLULAR MANUFACTURING: A REVIEW AND FUTURE DIRECTIONS

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Abstract

In this paper we review research that has been done to address cellular manufacturing under conditions of multi-period planning horizons, with demand and resource uncertainties. Most traditional cell formation procedures ignore any changes in demand over time caused by product redesign and uncertainties due to volume variation, part mix variation, and resource unreliability. However in today’s business environment, product life cycles are short, and demand volumes and product mix can vary frequently. Thus cell design needs to address these issues. It is only recently that researchers have been modelling uncertainty and multi-period issues. In this paper we conduct a comprehensive review of the work that addresses these issues. We present mathematical programming formulations as well as a taxonomy of existing models. Finally we suggest some directions for future research.

Keywords: Facilities planning and design, manufacturing, flexibility, robustness, product life cycle
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1.0 INTRODUCTION

In order to be successful in today's competitive manufacturing environment, managers have had to look for new approaches to facilities planning. It is estimated that over $250 billion is spent annually in the United States alone on facilities planning and re-planning (Tompkins et al., 2003, p10). Further, between twenty and fifty percent of the total costs within manufacturing are related to material handling and effective planning can reduce these costs by ten to thirty percent (Tompkins et al., p10). Thus considerable benefits may be obtained from effective and innovative approaches. These benefits are discussed in papers such as Meller and Gau (1996) and Benjaafar et al. (2002). One innovative approach to facilities planning is called Group Technology (GT). GT is based on the principle of grouping parts into families based on similarities in design or manufacturing. This paper focuses on cellular manufacturing systems (CMS), an important application of GT.

Manufacturing cells are created by grouping the parts that are produced into families. This is based on the operations required by the parts. These cells, which consist of machines or workstations, are then physically grouped together and dedicated to producing these part-families. Cells combine the advantages of flow shops and job shops with characteristics such as reduced cycle times compared to jobs shops and increased flexibility and greater job satisfaction.
as compared to flow shops. A recent example of CMS implementation at Canon is reported in Dreyfuss (2003). Canon, a major electronic equipment maker with 54 plants in 23 countries manufacturing cameras, printers and copiers, recently implemented CMS in all of its assembly lines. As a result, work-in-process (WIP) inventory in its factories has been reduced from three days to six hours. Factory operating costs have been reduced by US$ 1.5 billion. Canon has decreased its real estate costs by $279 million because cells require less room, and because the reduced inventory level has resulted in fewer required warehouses (down from thirty seven to eight).

CMS have some disadvantages however. Machines utilization may be lower due to dedication. Significant training is required in order to operate cells effectively. Further, when system uncertainty is present and product life cycles are short, cell reconfiguration may be an issue.

Various approaches have been suggested for forming manufacturing cells. Good discussions of CMS can be found in Burbidge (1963), Suresh and Meredith (1985) and Selim et al. (1998). Techniques range from the simple to the sophisticated and flexible. The simple techniques usually manipulate part-machine matrices. The sophisticated ones can handle many constraints in forming cells such as maximum cell size, different demands for different products, number of cells and set-up costs.

However, most of these methods assume that the part demand stays constant over long periods of time. But in today's market based and dynamic environment, part demand volume and part
mix can change quickly. Agility is required. For example, 75% of Hewlett Packard’s (HP) revenues are from product models that are less than three years old, and this percentage is increasing (Hammer, 1996, p212). In fact HP now uses specialized forecasting methods for its short life cycle products since traditional forecasting methods are no longer sufficient (Burruss and Kuettner, 2003). In a study of thirty two manufacturing cell life cycles at fifteen plants, Marsh et al. (1997) found that layout changes could occur as soon as within six months of the start of the cell life cycle. Thus when manufacturing cells are created, expected changes in products as well as uncertainty in demand and product mix have to be considered.

In this paper we review and categorize research that has been done to address cell reconfiguration and uncertainty issues in CMS. We first describe a deterministic model where we anticipate planned changes for the CMS due to planned product changes. We then discuss research that addresses this issue. Subsequently we discuss the issue of uncertainty in demand or product mix and the different approaches that can be used to address these issues. Finally we identify some directions for future research. Figure 1 shows our categorization of the different issues that exist in this area. We have also used this framework to guide the discussion of the different research studies that have been done. The categorization of the various research papers that have been published in this area is found in the Appendix, ordered by category. Some research of course may fall in more than one category.

This paper is written to meet the needs of researchers and practitioners who wish to study CMS under dynamic conditions. It helps decision makers understand the tradeoffs between the
different models that have been proposed and choose the appropriate technique for their situations.

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Figure 1: Categorization of multi-period planning and uncertainty issue in CMS
2.0 MULTI-PERIOD PLANNING WITH CELL RECONFIGURATION

2.1 Problem Formulation and Past Work

As stated, shorter product life cycles are an increasingly important issue in cellular manufacturing. One cannot assume that the designed cells will remain effective for a long time. Ignoring the planned new product introductions would necessitate subsequent ad-hoc changes to the CMS causing production disruptions and unplanned costs. Thus one has to incorporate the product life cycle changes in the design of cells. This type of model is called the multi-period CMS. In this model, we assume that a reasonable forecast of new product introductions, and part mix or volume changes can be made so that a multi-period plan is possible. For a review of the general multi-period layout planning models see Balakrishnan and Cheng (1998).

An example of a four period cellular manufacturing problem based on the dynamic plant layout model of Rosenblatt (1986), is shown in Figure 2.
Let $X$ be the optimal cellular configuration of the layout in period 1, with respect to the intercell transfer of parts. In period 2, if the product demand changes as explained previously, the optimal cellular configuration may also change. Let this be represented by $Y$ in period 2. Similarly, due to further demand changes in period 3, the optimal cellular configuration changes to $Z$. In period 4, the last period of the planning horizon, $Y$ may again be the optimal configuration. If there is no cost in changing from one optimal cellular configuration to another then the best course of action would be to use the optimal configuration every period. This would result in the most effective CMS within the multi-period horizon. But reconfiguring cells has associated costs such as moving machines, lost production time, and re-learning.

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Figure 2: The Multi-period Cellular Manufacturing System
So the reconfiguration decision should be taken only after a cost-benefit analysis. Further, using the wrong CMS configuration in a period may result in excess reconfiguration costs in subsequent periods. Thus there are two types of conflicting costs and the objective in determining a multi-period cellular configuration plan is to minimize the sum of these over the planning horizon. Due to reconfiguration costs, it is possible that a sub-optimal cellular configuration is the best one to use in a period as using this sub-optimal cellular configuration might result in lower reconfiguration and overall costs. For example, cellular configuration X may be optimal in period 2, but we use configuration Y because it lowers the overall multi-period cost. Since a sub-optimal cellular configuration may be used in a period, we have to examine every possible cellular configuration implicitly or explicitly in order to ensure overall optimality. Thus, when creating manufacturing cells it is important to take into account not only the interactions between machines but also the changes in product demand. Otherwise the cells may become outdated quickly resulting in excess costs.

Wicks and Reasor (1999) identify three common objectives to be met when designing the multi-period CMS, i.e., 1) minimizing the inter-cell transfer of parts, 2) minimizing duplication of machines, and 3) minimizing the between-period reconfiguration of cells. Subcontracting firms are good candidates for this model as these firms produce a variety of parts for a number of customers (Drolet et al. 1996). The integer programming formulation of Wicks and Reasor is shown below. Let
\( i = \text{index of parts}, i = 1, 2, \ldots, N; \)
\( j = \text{index of machines}, j = 1, 2, \ldots, M; \)
\( k = \text{index of cells}, k = 1, 2, \ldots, C; \)
\( l = \text{index of periods}, l = 1, 2, \ldots, P. \)

System parameters:

\( D_{il} = \text{demand (production volume) for part } i \text{ in period } l; \)
\( S_{il} = \text{number of processing operations for part } i \text{ in period } l; \)
\( O(i,r,l) = \text{machine type required by the } r\text{th operation on part } i \text{ in period } l; \)
\( T_{ijkl} = \text{processing time of part } i \text{ on machine type } j \text{ in period } l; \)
\( M_j = \text{number of type } j \text{ machines available at start of planning horizon}; \)
\( C_j = \text{capacity of machine type } j; \)
\( P_{jl} = \text{cost of acquiring a type } j \text{ machine in period } l; \)
\( H_{il} = \text{intercell per unit material handling cost for part } i \text{ in period } l; \)
\( R_{jl} = \text{cost of relocating machine type } j \text{ in period } l; \)
\( LM = \text{minimum number of machines per cell}; \)
\( LP = \text{minimum number of parts per family}; \)
\( A = \text{a large number} \)

Decision variables:

\( x_{ikl} = 1 \text{ if part } i \text{ is assigned to cell } k \text{ during period } l; 0 \text{ otherwise;} \)
\( y_{jkl} = 1 \text{ if machine } j \text{ is assigned to cell } k \text{ during period } l; 0 \text{ otherwise;} \)
\( n_{jkl} = \text{number of type } j \text{ machines assigned to cell } k \text{ during period } l. \)
\( q_{il} = \text{number of inter-cell transfers that occur during the production of part } i \text{ during period } l; \)
\( b_{jl} = \text{number of additional type } j \text{ machines acquired at the beginning of period } l; \)
\( u_{jl} = \text{number of type } j \text{ machines that are relocated between period } (l - 1) \text{ and period } l. \)

The objection function and system constraints can be formulated as follows:

\[
\min Z = \sum_{i=1}^{N} \left[ \sum_{k=1}^{C} x_{ikl} \left( H_{il} D_{il} q_{il} \right) + \sum_{j=1}^{M} \left( P_{jl} b_{jl} \right) + \sum_{j=1}^{M} \left( R_{jl} u_{jl} \right) \right].
\]

where

\[
q_{il} = \sum_{k=1}^{C} x_{ikl} \left[ \sum_{r=1}^{S_{il}} (1 - y_{O(i,r,1)j} y_{O(i,r+1,i)j}) \right] \forall i, l.
\]
\[ b_{jl} = \max \left\{ 0, \sum_{k=1}^{C} n_{jkl} - M_j - \sum_{s=1}^{l-1} b_{js} \right\} \quad \forall j, l. \quad (3) \]

\[ u_{jl} = \sum_{k=1}^{C} \left[ \max\{0, n_{jkl} - n_{jk(l-1)}\} \right] - b_{jl} \quad \forall j, l. \quad (4) \]

subject to:

\[ \sum_{k=1}^{C} x_{jkl} = \min\{0, D_{jkl}\} \quad \forall i, l. \quad (5) \]

\[ \sum_{i=1}^{N} D_{iti} T_{iji} x_{jkl} y_{jkl} \leq C_j n_{jkl} \quad \forall j, k, l. \quad (6) \]

\[ \sum_{i=1}^{N} D_{iti} T_{ijl} \leq C_j \sum_{k=1}^{C} n_{jkl} \quad \forall j, l. \quad (7) \]

\[ \sum_{j=1}^{M} y_{jkl} \geq LM \quad \forall k, l. \quad (8) \]

\[ \sum_{i=1}^{N} x_{jkl} \geq LP \quad \forall k, l. \quad (9) \]

\[ n_{jkl} \leq Ay_{jkl} \quad \forall j, k, l. \quad (10) \]

\[ x_{jkl}, y_{jkl} = \{0,1\} \quad \forall i, j, k, l. \quad (11) \]

\[ n_{jkl} \geq 0, \text{ integer} \quad \forall i, j, k, l. \quad (12) \]

The overall objective of the formulation is to minimize the total system cost (Equation (1)). The total system cost consists of the material handling cost (first term in the objective function), capital investment (second term), and relocation costs (third term). Equation (2) describes the inter-cell transfers per part, in a period. Equation (3) shows the number of machines acquired for
each period in the planning horizon. Equation (4) states the number of machines relocated for each period in the planning horizon. Constraint (5) ensures that each part is assigned to exactly one primary cell and that a part is only assigned to a cell for periods in which demand exists for the part. Constraint (6) is the within-cell capacity constraint stating that the total capacity of each machine type assigned to a cell must be sufficient to process the part family assigned to the cell. Constraint (7) checks the entire system capacity. Constraints (8) and (9) enforce lower limits on the number of machines and the number of parts assigned to each cell. Constraint (10) ensures that the number of units of a given machine type in a cell is equal to zero unless the machine type has been assigned to the cell. Finally, the values of the decision variables are restricted by constraints (11) and (12).

Since the problem is nonlinear and difficult to solve for practical sizes, Wicks and Reasor suggest a genetic algorithm (GA) approach. The chromosome used in the algorithm is based on a single-period assignment of machines to cells. Within each period, each chromosome is further divided into cells. A part-to-cell assignment heuristic that minimizes the inter-cell travel is also used. The reproduction operator is a variation of the remainder stochastic sampling with replacement policy. The crossover operator uses a standard single- and two-point method. Some less fit children are allowed to survive and some mutation is allowed to provide diversity. The GA is validated against other existing single period procedures using standard test problem data sets and is shown to be effective.
They compare their method with a static CM approach using an illustrative problem. In the static method the cell is designed using the first-period demand only and there are no further rearrangements. When the part mix changes the new parts are introduced into the existing CMS based on minimizing the inter-cell transfers of parts. Results show that the multi-period approach with a planned rearrangement of cells performs better than the static situation.

Balakrishnan and Cheng (2005) suggest a two-stage method to solve this problem. Based on Figure, 1, the static CMS and rearrangement of the CMS are separated so that each is solved separately. Thus it is flexible in that the decision maker can use different preferred methods for each stage. In the paper the authors use a GA for the static phase and dynamic programming for the dynamic phase, but point out that any method may be used. They also do some sensitivity analysis in the dynamic phase to illustrate the use of the dynamic approach in helping to improve the CMS.

Drolet et al. (1996) briefly mention the development of a dynamic cellular manufacturing system (DCMS) as part of their discussion on the evolution of cellular manufacturing. This model trades off the cost of material handling and the cost of cell reconfiguration. In a subsequent paper in the same journal issue Rheault et al. (1996) expand on the Drolet et al. (1996) model. The system involves part routing and loading, and production scheduling and monitoring. This integer programming model of the DCMS also trades off material handling cost and reconfiguration. However it is not a multi-period integrated model. The model reconfigures the CMS based on current period demand as needed. Marcoux et al. (1997) compare DCMS model of Rheault et al.
to a conventional CMS (CCMS) using a case study. In the study it is assumed that the planning horizon is two weeks, but at the end of each week, the cells in DCMS (but not the CCMS) could be reconfigured if necessary. The costs are calculated based on a 10 week study and the DCMS proved significantly less expensive.

3.0 UNCERTAINTY IN PRODUCT MIX AND VOLUME

3.1 Problem Formulation

While the Wicks and Reasor model can be applied to situations where the plan for new product introductions, and product mix and volume variation, can be reasonably forecasted, in many cases uncertainty may exist. Consider the Canon example discussed at the beginning of the paper. Usually customers demand some sort of customisation in products such as printers and copiers. So manufacturers tend to run mixed-model assembly lines. Thus when designing a cell, it has to be ensured that the cell is effective for different models (varying part mix) and uncertain volume since it is often difficult to predict how successful a particular model will be. Additionally there may be resource uncertainties such as machine breakdowns.

The formulation of Harlahakis et al. (1994) is one approach to addressing this uncertainty. This formulation is discussed here. The cell formation problem consists of dividing the manufacturing shop into a set of manufacturing cells $C = \{c_1, \ldots, c_w\}$, such that the total inter-cell traffic of parts within the design time horizon $H$ is minimized. The definitions in the formulation are given below where underlined characters indicate random variables.
- The set of machines, \( M = \{M_1, ..., M_g\} \) and their capacities, \( CM_j, j = 1, ..., g \).
- The set of all manufactured (make) components, \( I = \{ p_{1a}, ..., p_{lu_i}, p_{2a}, ..., p_{2u_i}, ..., p_{nu_i}, \} \). Note that \( \{ p_{1a}, p_{2a}, ..., p_{nu_i} \} \) represent the finished products (final assemblies) while \( \{ p_{1l_i}, ..., p_{lu_i} \} \) represent the manufactured components or subassemblies of part \( p_{il_i}, i = 1, ..., n \).
- The stochastic demand of the finished products over the time horizon \( H \), \( D = (D_1, ..., D_n) \).
- The processing sequence (routing) \( r_{ia} \), of each make part \( p_{ia}, i = 1, ..., n, a = 1, ..., u_i \). The production routing specifies a unique sequence of machines employed during the part manufacture as well as the corresponding processing times. Alternative routings that may employ functionally similar machines for the production of a certain part are not considered.

Let \( \Delta_i \) be the production volume of end product \( p_{il_i} \) within the entire design horizon \( H \). Then the cell formulation problem is formulated as follows:

Minimize \( \mathbb{E}\left( T(\Delta_1, \Delta_2, ..., \Delta_n) \right) = \mathbb{E}\left\{ \sum_{r=1}^{w} \sum_{s=1}^{w} \sum_{i=1}^{n} \Delta_i x_i(r, s) \right\} \), \( \text{(13)} \)

subject to

\[ q_r < Q, \quad r = 1, ..., w \] \( \text{(14)} \)

\[ \sum_{i=1}^{n} \Delta_i \Theta_i \leq CM_j, \quad j = 1, ..., g, \] \( \text{(15)} \)

where

- \( T(\Delta_1, \Delta_2, ..., \Delta_n) \) is the inter-cell traffic.
- \( \mathbb{E}\{\cdot\} \) is the expected value of the expression in brackets.
- \( x_i(r, s) \) is the number of times the final product \( p_{il_i} \) or any of its make components \( p_{1l_i}, ..., p_{lu_i} \) have to be transported from cell \( c_r \) to cell \( c_s \) and is given by:

\[ x_i(r, s) = \sum_{a=1}^{u_i} z_{ia} y_{ia}(r, s), \] \( \text{(16)} \)

where \( z_{ia} \) is the quantity of components \( p_{ia} \) that are used to produce one unit of final product \( p_{il_i} \), \( u_i \) is the total number of make components of end product \( p_{il_i} \), and \( y_{ia}(r, s) \) is the number of times make component \( p_{ia} \) is transported from cell \( c_r \) to cell \( c_s \).
• $q_r$ is the number of machines in cell $C_r$.
• $Q$ is the maximum allowable number of machines per cell.
• $CM_j$ is the capacity of machine $M_j$.
• $\Theta_j$ is the cumulative processing time of part type $p_{ij}$ and all its make items on machine $M_j$ and is given by

$$\Theta_j = \left[ \sum_{a=1}^{u_j} \Theta_{ia}^{au} \right] / b_j + \sum_{a=1}^{u_j} z_{ia} \Theta_{ia}^{run}, \quad (17)$$

where $b_j$ is the average batch size for part $p_{ij}$ and $\Theta_{ia}^{au}$ and $\Theta_{ia}^{run}$ are the set up and run times of make item $p_{ia}$ on machine $M_j$, respectively.

All variables are expressed in terms of the same time horizon $H$.

Equation (13) ensures that on average the resulting machine-to-cell partition will yield the minimal inter-cell traffic. Traffic values with higher probability are weighted more by this criterion, while the entire range of feasible production volumes is considered. The first constraint (equation 14), maintains the cell size below a predefined upper bound $Q$. The second set of constraints (equation 15) reflects the limited machine capacities. The workload depends on the set-up and run times of the make products and their production volumes. In the following sections, different approaches to solve this and similar problems are discussed.

In the two models discussed it is assumed that explicit and implicit cost parameters are known. However this may not always be true in practice. For example, as machines become more technologically advanced, it is possible that moving them may become more expensive. One may not be able to predict these costs in advance. Further the cost of acquiring the machine itself
may vary. On the one hand they may become cheaper as the technology matures but the cost of inputs (such as steel required to make them) may be unpredictable. Further the material handling costs also may not be predictable given the rate of technological change. Thus it is important to examine the sensitivity of decisions to changes in these parameters. Robust designs are another approach.

3.2 Robust Designs

The notion of robustness is initially studied in the general layout literature but can be adapted to CMS. The robustness of a layout is an indicator of its flexibility in handling demand variability.

3.2.1 General Facility Layout

Shore and Tompkins (1980) use a regret cost criterion to design robust layouts. Given a set of demand scenarios and associated probabilities of occurrence, penalty costs (regrets) are calculated for candidate layouts across these scenarios. The most robust layout is considered to be the one with the lowest expected facility penalty. Rosenblatt and Lee (1987) measure robustness by whether a designed layout is within a $\Delta$% of the optimal solution for every possible demand scenario. Under uncertainty, it may be better to choose a layout which performs well under all possible situations rather than one that is optimal for one possible scenario (which may not occur) but does poorly in other possible scenarios.

Kouvelis et al. (1992) address the problem of uncertainty by using the concept of robust layouts. Their method involves using a branch and bound (B&B) procedure (terminated before optimality in large problems) for finding a list of solutions in each period that is within $\Delta$% of optimality. In
another version of the stochastic layout problem, Rosenblatt and Kropp (1992) convert demand scenarios and associated probabilities of occurrence into one weighted flow matrix to solve the problem. Tests shows that this solution is robust giving good solutions in over 25,000 different scenarios.

Yang and Peters (1998) consider a multi-period model with alternate production scenarios and associated probabilities. The problem is solved deterministically using a mathematical programming formulation that uses the weighted flow matrix where the weights are the probabilities. In their model a rolling multi-period horizon is used where the layout can be rearranged at the end of each period. They consider different time horizons from zero to time period $T$ to find the best time horizon. If the time horizon considered is short, the layout is rearranged more frequently (called a flexible layout plan), while if it is $T$, then it is a ‘robust’ layout since the same layout is used for the entire planning horizon. Thus, it is considered appropriate for the different demand scenarios in each period. Tests show that the flexible layout reduces inter-cell transfer cost compared to the robust layout.

Afentakis et al. (1990) model a flexible manufacturing system using simulation. The main objective of the research is to compare a strategy of reconfiguring a layout every $n$ periods (periodic policy) with a strategy of rearranging it when the product volume, product mix or product routing changes by a threshold percentage value (threshold policy). The volume of parts and stability of this volume along with the frequency of change in the part mix are also considered. In this research, the authors use material handling and reconfiguration costs as
separate measures of performance. The results show that given a dynamic situation, the material handling performance deteriorates as \( n \) increases in the periodic policy and as the threshold percentage increases. Also when the part mix changes, the threshold policies work better than the periodic policies. Overall, the results show that a poor layout can add as much as 36\% to the material handling requirements. Therefore, given that FMSs are installed to perform better than job shops or dedicated lines under conditions of uncertainty, it is important to monitor them continuously on a layout basis to ensure its efficiency.

3.2.2 Cellular manufacturing

In CMS, Tilsley and Lewis (1977) address the issue of uncertainty in demand by using a ‘cascading’ strategy. A cascading system of cells is one where each cell is a child of another cell. The child cell consists of some machines similar to those of its parent cell along with some additional machines. If variable demand or mix changes result in the parent cell not being able to cope, the parts can be rerouted to one of the child cells giving the CMS flexibility.

Seifoddini (1990) incorporates probabilistic demand in designing the CMS. Each product mix and the related part-machine matrix are assigned probabilities. For each product mix considered, the best cell configuration is determined. Subsequently for each of these best cell configurations the expected inter-cell material handling cost based on possible product mixes is determined. Finally that cell configuration with the lowest expected inter-cell material handling cost is selected as the preferred CMS. This is considered a robust layout. Later Seifoddini and Djassemi (1996) conduct a simulation study of a CMS where the part mix changes to illustrate the
sensitivity of the CMS to part mix changes. This sensitivity analysis can help the decision maker predict the performance of a CMS under uncertainty.

Harlahakis et al. (1994) also consider product demand changes during a multi-period planning horizon. They focus on robust cells by designing a cellular configuration using mathematical programming based on expected values that would be effective over the ranges of demand during multiple periods. Once the cells are designed they are expected to remain unchanged during the multi-period horizon.

Marsh et al. in their survey of cell manufacturing life cycles discuss firms’ ‘hard and soft coping mechanisms’ in dealing with environmental changes in a CMS. Examples of hard coping mechanisms include the use of numerically controlled machining centres and tooling upgrades. Example of soft coping mechanisms would be worker cross-training and set-up reduction.

3.2.3 Robust Multi-period Plans

Montreuil and Laforge (1992) consider a set of probabilistic future scenarios in designing the layout. Initial skeletons are proposed and the relative positions of the departments do not change in later periods. Only the shape and sizes of the departments change. As well the size of the facility may also change. While these initial skeletons may appear to restrict the model, the authors suggest an interactive approach in which different skeletons for the different futures can be used. This is possible as the model is linear and thus large problems can be solved. The model
gives the resulting optimal layout for each future scenario in the scenario tree. The authors suggest testing the robustness of the proposed layout tree by performing sensitivity analyses on aspects such as the probabilities of occurrences of each future, the design skeleton, and the structure of futures of the tree.

Palekar et al. (1992) extend the product life cycle based work of Rosenblatt (1986) by considering the stochastic dynamic plant layout problem where they convert different demand scenarios into one weighted (by probabilities) flow matrix.

3.3 Part reallocation

Petrov (1968) addresses the issue of part mix changes in CMS by describing procedures used in the former Soviet Union. He describes an algorithm that allocates the new demand to existing cells. Though he indicates that issues such as common set ups should be considered in this allocation, his algorithm does not consider these issues.

Vakharia and Kaku (1993) incorporate long-term demand changes into their 0-1 mathematical programming cell design method by reallocating parts to families to regain the benefits of cellular manufacturing. New parts are allocated to existing cells. So cells are not rearranged in their multi-period design. While they discuss the possibility of partial or complete cell redesign they do not adopt these strategies, to avoid system disruption. They formulate this problem using an integer programming model. Since the problem is difficult to solve optimally it is solved heuristically using a limited enumeration method. The method is validated using pilot
problems where the optimal solutions are obtained. The results show that the heuristic is effective and efficient.

They also conduct a detailed experiment using seven existing data sets, three of which are industry based. Stochastic part demand and processing times are generated using the uniform distribution. The experiment consists of two parts. The first part examines the effect of factors such as machine duplication cost, material handling cost, demand and mix changes, the number of cells created and the routing flexibility (in terms of the ability of different cells to handle different parts). It is found that changes in part volume require more duplication of equipment than changes in part mix. Additionally if the CMS has low routing flexibility, changes in part mix result in greater inter-cell movement than changes in part volume. This is reversed for high routing flexibility. This indicates a tradeoff in handling volume changes versus mix changes.

The second part investigates robust designs by examining the effect of cell sizes and numbers on robustness. Different volume and part mix levels are considered. In general the results show that if the cell capacities in the initial preferred designs are not equal, then designs with larger number of cells are more robust because they can handle different capacities. For designs with equal cell capacity, fewer cells are more robust. This is as a result of less inter-cell movement. For part mix changes, in addition to smaller number of cells, high routing flexibility also contribute to robustness.

Askin et al. (1997) have proposed a four-stage algorithm that designs cells to handle variation in
the product mix. Initially a mathematical programming based method is used to assign operations to machine types. Subsequent phases allocate part-operations to specific machines, identify manufacturing cells, and improve the design. Experiments are also conducted to evaluate the effect of factors such as utilization and maximum cell sizes on the effectiveness of the algorithm. Again, cells once designed are expected to remain unchanged during the planning horizon.

3.4 Fractal Layout

Montreuil et al. (1999) and Venkatadri et al. (1997) discuss fractal layouts. A fractal layout converts a functional layout into physical cells as in a conventional CMS. But unlike a conventional CMS, the fractal layout procedure does not generally create cells based on product families. Rather it uses the ‘factory within a factory’ concept of Skinner (1974) with process duplication. Figure 3 shows the example of a fractal layout where the four fractals in the layout are identical. Thus all products can be processed in all the cells. However since having identical fractals can result in unnecessary duplication or under-optimized flow performance, it may be advisable to have fractals that are not identical (Montreuil et al., 1999). This is shown in Figure 4 where, though the fractals are similar, the layout within each fractal is different. As well, machines are being shared. Thus in general, fractals will have the ability to produce a wider variety of parts when compared to a traditional cell.

Montreuil et al. (1999) provide a conceptual discussion while Venkatadri et al. describe an integrated mathematical programming approach for creating fractal cells. The steps involved in
creating a fractal layout include capacity planning (on aggregate), cell creation, flow assignment, and cell and global layout. Montreuil et al. (1999) suggest setting the number of fractals a priori to the minimum number of copies of any of the machines.

Figure 3: Identical fractal layouts

They also suggest allocating machines to cells such that the composition of each cell is roughly equal. This leads to flexibility and can help respond to short term uncertainties such as machine breakdowns and varying product mixes. If a fractal is unique for each product family then the fractal layout basically becomes a pure CMS. Thus fractal layouts can range from a ‘factory within a factory’ concept to pure CMS.
Machines can be duplicated and shared if necessary to reduce inter-cell travel. Algorithms similar to those used to solve the Quadratic Assignment Problem (QAP) are used in the cell and global layout design phases. Montreuil et al. (1999) envisage that once a fractal layout is in operation, physical cell separation need not be enforced. Rather some operational and control mechanism such as a VCMS could be used. They also believe that fractal layouts provide great flexibility and robustness. In summary, the fractal layout is an attempt to disperse workstations throughout the facility in a meaningful way.

3.5 Virtual Manufacturing Cells

Many researchers have suggested the use of Virtual Manufacturing Cell Systems (VCMS) when product demand is uncertain or unpredictable. In a virtual (logical) cell, machines are dedicated to a product or a product family as in a regular cell, but the machines are not physically relocated close to each other. The paper by McLean et al. (1982) is one of the first to propose such an approach. An example of VCMS is shown in Figure 5.
In a VCMS, machines in a functionally organized facility would be temporarily dedicated to a part family. When a part requires processing it is routed to those machines dedicated to the part family. Thus as in physical cells, dominant flow patterns arise. Machines in the virtual cell are set up for that product family. If the demand pattern changes, the machines in any virtual cell can be reassigned to another part family. Since no machines have to be moved, there is really no rearrangement cost. This is an important advantage since using physical cells in the face of uncertain demand might result in cells having to be rearranged frequently on an ad-hoc basis. If the machines are not mobile, this could result in high costs (if the cells are reconfigured) or high inefficiency (if the cells are not reconfigured).
Thus, according to Kannan and Ghosh (1996a) virtual cells are ‘flexible routing mechanisms’. Virtual cells combine the advantages of both process layouts and cellular manufacturing. For example, one major disadvantage of traditional cellular manufacturing is that once cells are formed, the machines in a cell may not be available for parts not dedicated to that cell. Thus the machine utilization may suffer when compared to functional layouts, where machines can be assigned to any part at any time. VCMS avoid this drawback as the machine allocations are only temporary and can be reallocated easily (Prince and Kay, 2003). In addition in a VCMS, a family could have access to multiple machines of the same type. Subsequently if the need arises, some of these multiple machines can be reassigned to a part that needs it in order to ensure equitable sharing of machines (Kannan and Ghosh, 1996a). One aspect where VCMS would not have an advantage over physical cells is in the amount of travel since, in a virtual cell, the layout remains functional and the part may have to travel larger distances within the virtual cell.

3.5.1 Concept and Design

Drolet et al. (1989) and Drolet and Moodie (1990) discuss algorithms and scheduling in VCMS using production flow analysis (PFA), while Drolet et al. (1996) discusses VCMS within the context of the evolution of CMS. Kochikar and Narendran (1998) describe a mathematical programming based heuristic method to design a VCMS in an FMS.

Sarkar and Li (2001) using network optimization to design virtual cells where the objective is to
minimize throughput time. Instead of defining only one path they create the $k$ best paths. In order to achieve this they use a double sweep $k$-shortest path algorithm. A heuristic version of this algorithm is devised to solve more practical scheduling situations with multiple jobs, shared bottleneck machines, and precedence and resource constraints.

Ratchev (2001) describes an iterative and concurrent method for designing virtual manufacturing cells through four steps. The first step involves identifying component requirements and generating processing alternatives. Then the boundaries of the virtual cell capabilities are defined, following which the machine tools are selected. The final step is system evaluation.

Prince and Kay (2003) discuss the use of virtual groups (VG) to enhance agility and leanness in production. Both VCMS and VG use the concept that machines in a cell need not be physically located close to one another. However, while VCMS focuses on managing the process, VG focuses on the management of products from design to production. So the relationship of VCMS to VG is somewhat analogous to the relationship between CMS and GT. GT is a much broader concept than CMS and in fact includes CMS as its component. GT involves among other things, part family identification, engineering design rationalization and variety reduction, and process planning (Suresh and Meredith). Similarly in VCMS, it is assumed that the routing has been provided and what is necessary is to identify the virtual cell required. There is no proactivity in designing and process planning to make products fit into existing cells. The machines are managed more like a jobs shop than a CMS, i.e, teams are directly in charge of machines or machine groups but not products. Thus there would be handoffs from team to team in the
completion of a product which leads to discontinuities in the management of the production.

In a VG, as in GT, product group managers would be assigned a team of operators and all the machines required (though physically distributed within the facility) to make complete products or major subassemblies. They could be responsible for managing the product right from design, through process planning, creation of the virtual cells and order completion. The advantage in VG over VCMS is that VG is much more broad based and proactive in concept making planning and scheduling more effective. Further Prince and Kay believe these groups are likely to be longer lasting than in VCMS. This would make it easier to implement lean and agile concepts in the different stages of production. In addition in VCMS, different machines in a group could be managed by different groups, thus not utilizing the advantage of teams. Thus VG are an attempt to improve upon some of the disadvantage of VCMS.

### 3.5.2 Comparison of VCMS to other Manufacturing Systems

In comparing VCMS to traditional CM, Subash Babu et al. (2000) categorize CM benefits into three categories: (1) human related factor benefits from empowerment in smaller cells, (2) improved flow and control in cells due to having to deal with smaller number of parts and machines, and (3) improved operational efficiency due to similarities, in terms of reduced setups, smaller batch sizes, increased quality, productivity, and agility. They suggest that VCMS do not offer benefits in the first category, while providing considerable advantages in the second
Kannan and Ghosh (1996a, 1996b) compare different VCMS to CM and process layouts using simulation. Different configuration rules for VCMS are considered. These include rules such as: for a machine, giving allocation priority to a family with lower average slack per job, or to a family with the fewest remaining machines needed to complete a cell. Inter-family setup times are higher than intra-family setups as is common in practice. The demand patterns show variability (uncertainty) through part mix and volume changes. Set up times and shop load are also varied. Primary performance measures include mean flow time, mean tardiness and the mean and standard deviation of the WIP.

The results show that VCMS perform better than both the process layout and CMS, over a wide range of conditions and is more robust with respect to demand variability. When there is less demand uncertainty, the cellular advantages of VCMS are utilized, while when demand uncertainty is high, the VCMS’ ability to quickly reconfigure the cells is utilized. The simulation shows that VCMS allows jobs to spend less time in queues and setups as compared to process layouts due to dedicated routings and shared family setups. It is also shown that some of the VCM rules perform worse than the others. Kannan (1997) further investigates the effect of family configuration on VCMS performance.

Vakharia et al. (1999) use queueing theory (using stochastic arrival and service rates) to
examine the performance of VCMS with multi-stage flowshops. The number of processing stages, the number of machine copies at each stage, batch sizes and ratios of setup times to run times per batch are varied. The virtual cells are manually created. In the VCMS setup time is zero since each machine is a priori dedicated to a part family. In the multi-stage flowshop a part may be routed to any of multiple copies of a machine in each stage. The results show that VCMS are not always better that multi-stage flow shops with respect to flow times. For example, when setup to run time ratios are high VCMS have an advantage as expected. But for large batch sizes and greater number of stages, VCMS have higher flow times (poorer performance) than multi-stage flow shops due to lack of routing flexibility and increased queue times. An industrial application confirms the results that VCMS may not be appropriate for all stages. Rather a combined system may work better.

While VCMS have advantages over CMS, it is unable to take advantage of some of the human related factors as stated by Subash Babu et al. Human factor advantages are difficult to evaluate through computer simulations such as that of Kannan and Ghosh (1996a, 1996b), and sometimes tend to be overlooked. Important human factors aspects of CMS include team building, learning, and problem solving. These would be difficult to do without physically grouping cells together.

For example, one company in the maintenance, repair and overhaul (MRO) industry that one of the authors in familiar with uses CMS. Outside each cell, a board showing performance indicators such as lead time, WIP, and bottleneck measures is posted. Thus any deterioration in performance can quickly be identified and corrective measures taken. In a VCMS where
machines are not grouped together, such a posting would be difficult. In addition, in a VCMS, just as in a process layout, it is not clear who would be responsible for improvement, since employees work on individual machines and are not responsible for the entire routing. In CMS, the team managing the cell would be responsible for the performance.

HP (Hewlett-Packard, 1984) is another example of a company that uses CMS for facilitating problem solving. Cell team members regularly spend time brainstorming and solving problems within the cell to improve productivity and quality. This would be more difficult in a virtual cell since team members may be working in different areas of the facility and may not work in proximity to each other.

Thus VCMS is based on the recognition that in the current manufacturing environment of uncertainty and short product life cycle, agility is important. VCMS in general appear to be more agile than CMS. In terms of layout, the research on VCMS has usually assumed that the existing job shop layout is not reorganized. However, as mentioned, physically grouping machines has its advantages. Thus in the next sections we discuss three innovative layout approaches that have been suggested in the literature that can facilitate the use of VCMS, while reducing some of the disadvantages of VCMS. These include distributed, holonic and fractal layouts. All these layouts involve some reorganization of the job shop layout but not as much as would be done in a CMS.
3.5.3 Distributed Layout

Benjaafar and Sheikhzadeh (2000) and Benjaafar et al. (2002) suggest that a distributed layout might help in VCMS. In a distributed layout, machines of the same type are not grouped together as in a process layout but they are distributed throughout the facility individually or in clusters. In a maximally distributed cell individual machines of the same type from a job shop layout would be distributed uniformly in the facility as in Figure 6b. The maximally distributed layout is the same in concept as a holonic layout proposed by Montreuil et al. (1993) which is discussed in the next section. In a partially distributed layout each functional department is split into subgroups and distributed throughout the facility and may have duplicate machines (Figure 6a). Thus when creating a virtual cell, the required machines from clusters that are located close to each other can be selected. While still not a physical cell, the distance traveled by the part in its routing can be reduced by using distributed layouts as compared with pure process layouts. Earlier Figure 5 was used to illustrate a maximally distributed layout with virtual cells.
Benjaafar and Sheikhzadeh discuss a distributed layout model to design a flexible layout under the conditions of varying product mix and product demand. They use mathematical programming (heuristically) to minimize the material handling cost given different scenarios. In this model, the distribution of machines is not maximal. It is distributed based on the process routing for products and the material flow between department types. Once set up, the control would be similar to a VCMS where cells are created and disbanded as needed. Tests show that this type of weighted layout performs better than both functional and maximally distributed layouts.

Figure 6: Distributed layouts

(a) Partially distributed layout
(b) Maximally distributed layout
layouts. Thus it illustrates that including flow information in designing distributed layouts is beneficial. They do caution that these benefits have to be traded off against losing the economies of scale that exist in a job shop with respect to operators, loading/unloading, and computer control which may have to be duplicated across all machine copies in a distributed layout. Lahmar and Benjaafar (2002) extend this model for multi-period planning where the layouts can be rearranged at the beginning of each period.

3.5.4 Holonic Layout

As mentioned, Montreuil et al. (1993) introduced a concept called holographic or holonic layouts (Figure 6b). It is a subset of distributed layouts where individual machines are distributed through the facility. It comes from the Greek words **holos** for whole and **on** for part. The word **holon** was coined by Arthur Koestler (1968) to describe the basic unit of an organization in a social or biological system. In a holonic layout, a machine (**holon**) that has no duplicate would be placed in the center of the layout, while machines with more duplicates would be strategically placed throughout the factory floor. The objective is to provide efficient process routes for any part type that the system may need to produce with a minimum of delay. Montreuil et al. (1993) describe a heuristic that attempts to spread machines of each type as evenly as possible throughout the shop. As new orders arrive, routings are generated by searching for compatibility between part requirements and machine availability, location, and capability. Thus the operation and control is similar to VCMS. Like distributed layouts this makes the layout robust in the face of agile environments. Marcotte and Montreuil (1995) describe a procedure to form holographic layouts that assumes that information such as the
frequency of machine type to machine type transfers is known. These would be derived from the process plans and demands. The process also includes selection of machine routings for products as well as machine location.

Askin et al. (1999) compare process, holonic and fractal layouts using computer simulation. The fractal layouts are selected to be identical as possible in the number and the type of machines. The relative location of each machine in a fractal is random. In the holonic layout the machines are either located throughout the facility randomly or by using a similarity coefficient method where related machines are located close to each other.

Since incoming jobs have to be routed, different rules are considered, such as existing queues, bottleneck avoidance or least total workload. For the fractal layouts, once a job goes into a fractal it is completed in the fractal. In the holonic layout, static and dynamic (based on real time information) rules are considered, where machine selection is based on existing queues and travel time to candidate machines. For the process layout a job goes into a common queue for the selected machine type. The layouts are simulated under various conditions of processing time, move times, demand rates, plant sizes, number of processes, sequence selection, and utilization. Cycle times are the primary performance measure.

The results provide insight into the comparative performance of different types of layouts. As expected when move times are low process layouts perform better than holonic layouts. This
implies that process layouts are preferred to VCMS since holonic layouts are a form of VCMS. In turn the similarity coefficient based holonic layout using dynamic scheduling rules performed better than the fractal layout which is a form of CMS. This is due to the pooling effect of common queues and the irrelevance of travel times due to its small magnitude. Thus if moves can be done fast or move distances are short, then it appears that the flexibility of the traditional process layout overrides the VCMS and CMS based attributes of the holonic or fractal layouts respectively, at least in terms of cycle time.

For larger move times the fractal and holonic layouts performed better than process layouts. The fractal layouts gave lower average cycle times than process layouts and holonic layouts, due to the benefits of within cell processing similar to a CMS. Also choosing the fractal layouts based on total workload, rather than number in queue or bottleneck avoidance provides better results. However the similarity coefficient based holonic layout using dynamic routing rules was the most robust, proving to be flexible and reliable under a variety of conditions.

Thus the holonic layout proved to be a good compromise between the flexible but longer travel characteristics of process layouts and the less flexible but shorter travel characteristics of the fractal layout which is more CMS like. Thus this research supports the notion that a VCMS is a good compromise between process layouts and CMS. However, it was also shown that holonic layout design was an important factor in its success since the random distribution if machines resulted in poor results while the similarity coefficient based distribution gave good results. It also appears that real time information in scheduling (deciding which machine to go to after it is
processed on the previous machine) is important for holonic layouts to be effective. This was not an issue in fractal layouts, since as in a CMS, products sent to a fractal (cell) stay in that fractal. Though partially distributed layouts have not been compared experimentally to holonic or fractal layout, it is likely that the performance would depend on how ‘partial’ it is. The more the partially distributed layout is similar to a process layout, the more it is likely to be preferred to holonic or fractal layouts for smaller move times. As seen in figure 6a, since each sub-group of similar machines has multiple copies, the pooling effect of common queue as in a process layout will be advantageous. If the layout is closer to the maximally distributed layout shown in Figure 6b, then it will have the advantages of a holonic layout which was effective for large move times. As mentioned, in this case, actual distribution of machines as well as real time information based scheduling is important.

3.6 Hybrid Cells

Irani et al. (1993) describe a hybrid CMS which retains some aspects of a functional layout while at the same time allocates machines to part families. It allows for overlapping of routes, and differing cell allocations to accommodate volume variation, machine breakdowns, mix changes or other uncertainties. Thus it has characteristics of a VCMS also.
Figure 7: Types of layout: a) Functional Layout, b) Cellular layout c) Hybrid cells


Legend: T: Turning; M: Milling; D: Drilling; SG: Surface Grinding; CG: Cylindrical Grinding
Figure 7a shows a regular functional layout. In Figure 7b, the functional layout has been converted into a CMS. One problem with the CMS is that if the part mix changes, the volume is larger than expected or machines breakdown, then rerouting may become a problem. For example assume that due to excess volume an additional drilling machine (D) is needed for the cell with the square part. To access another D, the part may have to travel across two cells where the closest D is located. This of course is not desirable from a material flow perspective. To avoid this in Figure 7c, the cellular layout has been redesigned so that machines of the same type are still close together as in a functional layout. For example, all D’s are close together. So this layout, called a hybrid layout provides the benefits of CMS and the routing flexibility benefits of the functional layout. This also allows for flexibility by allowing machine to be allocated to different part families in successive production periods through the use of tools and fixtures. Thus it shares characteristics of a VCMS also, where the family-machine allocation changes over time depending on the demand. Irani et al. (1993) also present an effective mathematical programming based technique to design such cells. The benefits of hybrid layout is supported by a survey by Wemmerlov and Hyer (1989). It shows that sharing of machines appeared to be popular in practice with 20% of manned cells and 14% of unmanned cells in the companies surveyed doing so.

Hybrid layouts have not been experimentally compared to the other types of layouts. Conceptually, since it has the characteristics of a CMS, VCMS and process layouts it should be flexible. If the demand tends to be uncertain in terms of product mix and volume, one could avoid dedication of machines to part families and use it as VCMS with a process layout since the
layout involves characteristics of a process layout as shown in Figure 7c. On the other hand if product demand is stable, it could be operated as a CMS. If move times are low it could be used as a process layout as in Askin et al. (1999). Thus it could be used advantageously under various demand conditions. The challenge would be to design the layout such that the layout can physically have as much of the characteristics of a CMS and process layout as possible.

3.7 Modular Layout

Irani and Huang (2000) and Benjaafar et al. (2002) discuss modular layouts. A modular layout consists of a network of modules, each representing part of the facility, and each of which could be product, process or cell based. A product would have to move through one or more of these modules to be processed. Figure 8 shows a modular layout at Motorola.
The layout consists of different modules. Some are functional, while others are product based or cell based. The modular design arises from the fact that ideally each product should be produced in flow line which generally has the lowest cycle time. However this would result in too much investment in machine duplication. The next best alternative is to identify subroutings within the various products that are identical. These could then be produced on flow line as in high volume manufacturing. This could form a flowline module. Naturally there could be multiple such flow
line modules if product line of the facility is large or machine duplication is viable. Where the subroutings are not identical but have similar machine requirements, cell modules could be created. These could then be identical to a CMS with its advantages. However unlike a traditional CMS, note that only part of the product may be processed in a cell. Functional modules are similar to a process layout and might include machines that cannot be duplicated but are common to multiple part families. As in the process layout the routing of parts within the functional module would be random. Benjaafar et al. suggest from experience that product routings often have common substrings of operations that could be aggregated into flowline or cell modules.

The physical layout could be designed so that products move between adjacent modules to avoid unnecessary travel. If the product mix changes, the routing of a product between different models would change. This might necessitate addition or deletion of modules as well as rearrangement of the layout. Irani and Huang (2000) present mathematical programming formulation that minimize the sum of inter-module travel and machine duplication. However since it is NP-complete, they provide a heuristic method based on string matching and clustering using similarities. They used the method to design a modular layout for Motorola. The advantage of modular layouts is that they use the advantage of flow lines and cellular layouts as much as possible while retaining the flexibility to produce different type of products or different volumes efficiently.
3.8 Routing Flexibility

Gupta and Tompkins (1982) use simulation to study a CMS under the effect of part mix changes and alternate routings. When a new order comes in, alternate routings (within and outside cell) are considered if its regular routing will not allow it to be completed by the due date. Rerouting to another cell results in a time penalty to reflect the ineffectiveness of the alternate cell. After the completion of one operation the job continues on its original routing.

The results show that inter-cell moves are significantly lower for larger cell sizes since alternate routings can be found within the cell. The authors caution that having very large cells would result in both transportation and cell management disadvantages. An interesting observation is that alternate routings may not always be advantageous. If the alternate route is inefficient, the job may take more time. In this case it may be better to queue it in the most effective cell since the queue times may be less than the additional process and transportation times incurred in ineffective cells. However the results also show that queues tend to cause longer system disturbances than alternate routings. The authors suggest a forward looking MRP system to help plan re-routing ahead of time.

Ang and Willey (1984) compare hybrid cells to pure CMS using computers simulation. In a hybrid CMS inter-cell transfer (alternate routing) is allowed. In their research design, if the average workload at a machine exceeds a set threshold upon the arrival of another job at the machine queue, a search is done to identify a suitable job that can be routed to another cell to
balance the overall workload. Different heuristics are used to identify this job. The job that is moved to the other cell incurs additional material handling and is completed in the new cell if possible. Different shop configurations and job dispatching rules are tested. Job mix and arrival rates vary. Performance measures include mean job flow time, mean job tardiness, and the standard deviation of mean job lateness.

Results show that inter-cell transfer, specifically at a low level, significantly improves performance measurements under all conditions. Thus this inter-cell transfer allows the CMS to respond better to part mix and volume variation. In addition batch overlapping (feasible in a CMS due to the proximity of machines in a cell) works effectively in tandem with inter-cell transfer. Thus hybrid cells prove to be more effective than pure cells.

Jensen et al (1996) compare three types of layouts – a functional job shop, a pure cell shop and a ‘routing flexibility’ (RF) cell shop. In the pure cell shop, all part operations are dedicated to a single machine of a given type. All processing is completed within a single cell. There is no routing flexibility. Thus it is similar to a product layout with dedicated machines and low set up costs because of the dedication. An RF cell shop is a compromise between the functional shop and pure cell shop. It has fewer cells than a pure cell shops, which implies that some cells can have duplicate machines of the same type, as in a functional shop. But since each cell does not process as many families as a functional shop, there is more dedication of machines leading to lower set up costs and routing lower flexibility than the functional shop but more than a pure cell shop.
The comparison is done using computer simulation under conditions of product mix and product volume variability and the measures are flow time and tardiness. The results show that the RF cell shop performs better than the other two types of shops under conditions of uncertainty. The routing flexibility combined with the set up efficiencies makes it attractive. Thus the RF cell design proves to be a robust design in the face of uncertainty in demand.

Albino and Garavelli (1999) investigate the concept of ‘limited flexibility (LF)’ proposed by Jordan and Graves (1995). In limited flexibility some alternate routing is allowed but not the complete flexibility that would be allowed if each part could be processed by each cell. The notion is to provide some flexibility to allow the system to be robust but at the same time to avoid the additional investment and management complexity caused by complete flexibility.

The simulation study is done with demand mix variation and resource availability variation due to factors such as machine breakdowns. Different loading rules are tested. The performance measures are the cost of lost sales and total cost. The cells are designed using mathematical programming. The results show that as system uncertainty increases, in general limited flexibility is preferred to total flexibility. However the results are sensitive to the resource unreliability, and the cost of adding routes versus the cost of lost sales.
Another way to achieve this flexibility is through the implementation of a flexible manufacturing systems (FMS), i.e., a system with routing and processing flexibilities (Lin 1993, Ho and Moodie, 1996). Studies by Lin, and Mehdi and Kurapati (1993) show that these systems can yield significant productivity improvement. If a CMS uses such systems then each cell would have much flexibility to handle uncertainties.

Meller and DeShazo (2001/2002) describe the implementation of Multi-channel Manufacturing (MCM), a form of CMS where products are designed to have multiple routings, at an electrical goods plant in the USA. The implementation of a cellular MCM (using some of the concepts of Tilsley and Lewis) provides significant benefits over the previous process layout system.

3.9 Flexibility and Performance in Different Layouts

Routing flexibility is a concept that relates to the layouts discussed so far. In fact many of layouts and manufacturing systems discussed here have an implicit or explicit objective of improving flexibility. The VCMS aims to increase flexibility by not physically reconfiguring cells. When the product demand changes, logical cells are created from the process layout as required. However as mentioned by Subash Babu et al. (2000), VCMS have the disadvantage that the human factor benefits may be less than that of CMS. Further it is logical to assume that improved human factor benefits may lead to increased flexibility in terms of producing multiple products in a cell, learning, improved quality and ultimately faster throughput.
Thus the implementation of a concept such as a VCMS can be enhanced by using innovative layouts. The distributed layouts (Figure 6a and b) are examples of such innovative layouts. By distributing the machines it may be possible to create cells such that the machines that process a part family are close to one another thus in effect creating a CMS. Then at least some of the advantages of the human factors aspects can be obtained. At the same time when product demand changes the virtual cells can be rearranged without having to move equipment. Thus distributed layouts may be useful where the cost of moving machinery is prohibitive. Where machines can be moved at a reasonable cost then a multi-period model similar to Wicks and Reasor (1999) can be used. The choice between different types of distributed layouts would depend on the tradeoff between queue times and move times. If the queue pooling benefits of partially distributed layout is more important than move times or human factor effects then it would be preferred to maximally distributed (holonic) layouts. In the holonic layout since individual machines are distributed more uniformly, there is a better likelihood than in the partially distributed layout of finding a cell for a product where the machines are located in close proximity. Thus would reduce move times and have better human factor advantages, though queue times might be greater. Thus these layouts can provide different levels of flexibility to a VCMS under different environments.

Similarly modular and hybrid layouts are an attempt to increase the flexibility of manufacturing systems under conditions of uncertainty. As mentioned earlier hybrid layouts have characteristics of process layouts as well as CMS. Thus depending on the situation they can be made to simulate process layouts or VCMS. However further study would need to be done as to how effective it
would be in practice to create a layout as in Figure 7c where the machines are grouped into cells while at the same time similar types of machines are in proximity of each other as in a process layout. For example, one might want to examine if this sort of a layout be more feasible in a larger facility with many machines or a smaller one. Also one might want to determine the ratios the number of copies of each machine type should be in to make this feasible.

Modular layouts are different from the others in that it explicitly attempts to have different types of traditional layouts within the same facility in order to improve flexibility. Conceptually modular layout should be a good option for managers, perhaps better than the other proposed layouts because of its combination of different layouts. None of other layouts proposed suggest combining flowlines, cells and process layout. Thus, this combination should provide many advantages. The flowline and cellular modules should help in reducing cycle times as opposed to a process layout. In addition the existence of process modules should help it address the issue of uncertainty. A one-off batch could be produced in the flexible process modules without affecting the manufacture of products in the other modules much. Similarly product changes can be accomplished by changing, adding or deleting modules without affecting the entire shop. The challenge is to find common subroutings for flowline modules and to design robust cell modules such that they can handle higher part variety without having to re-organize modules frequently.

On the other hand fractal cells are more similar to CMS in that they physically rearrange machines into cells. But the objective is again to increase flexibility and the could use VCMS as a control mechanism under uncertainty. As mentioned, if the cells are unique it becomes true
CMS with advantages and disadvantages. On the other hand if the cells are identical, a ‘process layout factory within a factory’, the main benefit as seen by Askin et al. (1999) is in the low travel times and in its flexibility in dealing with uncertainties such as machine breakdowns or volume changes due to its process layout characteristics. However in the case of high uncertainty in product mixes, the unidentical cell fractal layout may work better than the identical fractal layout. Consider a hypothetical Product 1 in an identical fractal layout (Figure 3) that is routed through machines A, B and D of Cell 1 in that order. If there is a breakdown in Cell 1 or the volume increases, since all the other three cells have an efficient A-B-D routing, the environmental change can be handled efficiently. In the unidentical layout (Figure 4) only one other cell has the A-B-D routing, and depending on the situation even this amount of duplication may not exist. Thus it is not as effective as the identical fractal layout. However, if Product 1 is replaced in the market by Product 2 requiring a routing of A-B-E, in Figure 3, such a routing does not exist in an efficient manner while in the unidentical fractal layout (Figure 4), an efficient A-B-E routing does exist in Cell 4. Thus in this case where the product mix has changed, the unidentical fractal layout can handle this environmental change better than the identical fractal layout. At the same time the identical fractal layout may be better than a true process layout since the different types of machines may be in closer proximity as in Figure 3. Thus cycle times will be faster and some the human factor advantages such team management of the entire production of the part may also be possible. However, as Montreuil et al. (1999) mention, an identical fractal layout may not be feasible because of excessive machine duplication costs.
Thus in practice one may use a fractal layout that is a mix of unique and identical. This may result in inter-fractal flows as shown in Figure 4. One important issue is in the design itself. In the industrial case study done by Montreil et al. (1999), three fractal were created and each of these could produce approximately one-third of the product line. This provided flexibility against system breakdowns and presumably against product uncertainty. At the same time flow reductions of 9% were achieved over pure CMS. Thus it appears that if fractal cells are properly designed they can result in significant improvements in flexibility without sacrificing the advantages of CMS such as low flow times. Another issue in fractal layout is that demand and product mix uncertainty since physical cells are being created. Montreuil et al. (1999) suggest the use of VCMS in operating and controlling the fractal cells, however they also suggest more research into how this might be implemented.

3.10 Multi-objective System Selection

All the layouts discussed so far have been designed with a single objective in mind, usually the minimization of the costs of material handling and machine investment. Moreover all the measures have been quantitative. However, often there may be a combination of qualitative and quantitative considerations in designing layouts. For example, while the human factor advantages of different layouts has been discussed in this paper it had not explicitly been modeled in any of the papers discussed. This aspect may be an important qualitative criterion in designing layouts and could be incorporated by the use of multi-objective methods in layout design.
Chan and Abhary (1996) combine cell formation methods, simulation and the Analytic Hierarchy Process (AHP) to select the appropriate the cell design for an automated CMS. AHP (Saaty, 1980) is a multi-objective decision support tool that uses specified weights and pair wise comparisons of different alternatives based on competing multiple attributes. The authors describe a case study in which four different cellular layouts are simulated to evaluate various performance measures such as lead times, utilization, costs, reliability and flexibility. Three cases with varying weights on the financial and non-financial attributes are tested. Some attributes such as lead times could be compared on a pairwise basis directly from the simulation results whereas interviews with plant personnel had to be done to make pairwise comparisons for attributes such as flexibility. Based on these comparisons and using AHP software they are able to determine the best manufacturing system. The same configuration is best in all three cases, thus indicating the robustness of the solution.

4.0 FUTURE DIRECTIONS

One of the advantages of pure CMS is that workstations are designed to be in proximity of one another, based on product flow. This opens opportunities for organizing teams of workers with decision making responsibilities. Teams may be involved in production planning and scheduling, quality management, and process improvement. As mentioned in the HP example, cell team members regularly met to discuss productivity and quality improvements. Future research needs to examine how these issues could be integrated with flexible cell design, which helps dealing with demand and part mix variations, but where machines may not be physically located to next to each other. Future case studies of the implementation of some of the procedures described in
this paper may shed lights on these issues.

Traditionally, there has not been much research in organizational behaviour issues in cellular manufacturing. One reason may be that these concepts are difficult to model (Morris and Tersine, 1990). However in recent years several researchers have highlighted the important interactions between human resources management (HRM) and operations management (OM), and the need to incorporate organizational behaviour issues in operations management. Boudreau et al. (2003) discuss the interface between HRM and OM in various operations management decisions. They provide references to previous work in the HRM/OM interface and conceptual frameworks for incorporating HRM concepts in OM and vice versa. A recent special issue of Management Science (Volume 49, Number 4, April 2003) focused on creating, retaining and transferring knowledge in organizations. Further, another special issue of IIE Transactions (Volume 36, Number 10, October 2004) dealt with workforce agility. Finally Boudreau (2004) presents a survey of papers that appeared in the first fifty years of the journal Management Science related to organizational behaviour.

Fazakerley (1974) through studies at multiple facilities in the United Kingdom suggests that the following personnel problems may occur when CMS is introduced: 1) uncertainty and insecurity, 2) management’s lack of understanding of CMS, 3) lack of team work within cells, 4) tendency to become complacent and less innovative, and 5) problems with the compensation system. One could examine how these issues affect CMS innovations such as VCMS, holonic layout, or distributed layout, which are more sophisticated concepts than a pure CMS.
Shafer et al. (1995) through a survey of employees at two manufacturing facilities compare the effect on employee perception and attitude of cellular manufacturing versus functional manufacturing. They find that cellular manufacturing has both positive and negative impact. Although the positive aspects can be explained by the fact that CMS job characteristics such as increased autonomy, flexibility, and responsibility increase job satisfaction, it is more difficult to explain the negative aspects. Shafer et al. speculate that any job problems that may exist are made more acute by CMS and that some employees may have difficulty in adapting to CMS. In essence they echo Fazakerley’s concerns. For example, employees who are not motivated towards growth in their career may not be ready to accept the uncertainty that accompanies increased autonomy, responsibility and flexibility. Further, in a process layout employees tend to work individually while in a CMS they tend to work in groups. If some employees are unable to work in groups or the groups do not function effectively, the results may be increased dissatisfaction on the part of these employees. Also if workers do not understand CMS concepts, they may not be convinced of the benefits of CMS implementation, resulting in change management issues.

One important aspect that has been shown to affect the performance of cellular manufacturing is learning. Learning curve theory, a good survey of which is done by Yelle (1979), indicates that the processing time required decreases with increases in repeated output. Thus the theory suggests that since in a CMS there is more job repetition than a job shop, there may be more learning and resulting shorter processing times in a CMS. Thus learning should be one of the
factors considered in comparing the two systems. Kannan (1996) shows that learning in a CMS allows it to overcome the disadvantages or reduced flexibility due to machine dedication to part families. Kannan uses the log-linear function (Wright, 1936) to model learning. Biskup and Simons (2004) call the model using the log-linear function, ‘autonomous learning’ while learning models in which management is actively involved is called ‘induced learning’. In induced learning management incurs an initial investment such as employee training to stimulate learning beyond the autonomous model. Biskup and Simons formulate and solve a mathematical programming model that optimizes the amount of initial investment for learning required to minimize earliness and tardiness. Kannan and Palocsay (1999) through the use of queueing models show that without learning, manufacturing cells may perform poorly when compared to job shops.

Researchers have also recently addressed an allied induced learning issue which is important in CMS, that of cross training. Jordan et al. (2004) use queueing and simulation to evaluate different cross training strategies for time required for completing repairs in the maintenance function. Bokhorst et al. (2004) use goal programming and simulation to investigate different cross training policies. In this paper the authors consider both HRM (minimizing the standard deviation of workload) and OM (minimizing flow time) measures. Kula et al. (2004) use queueing theory to model set-up operations with cross training and show that cross training has a beneficial effect on flow times.

Since both learning and cross training serve to increase the effectiveness of CMS, it would be
useful to investigate the effect of these factors when uncertainty is considered. For example, since virtual cells, hybrid cells and distributed, holonic, fractal layouts involve features of both CMS and jobs shops but in different ways, it is important to evaluate whether learning and cross training would have different effects under certainty and uncertainty. This could involve models previously used to evaluate these issues in general manufacturing such as queueing theory, computer simulation and mathematical programming. Also the impact of the incorporation of learning and cross training on the solution methods used in multi-period CMS models discussed in this paper is also an important issue. Furthermore, the importance of learning in cells depends on the nature of processes such as postponement, modular design, and product standardization, since they have different effect on the stability of CMS. This area requires future study.

One of the advantages of CMS is reduction in setups. Ensuring that setups do not become an issue again as they are in process layouts, when flexible layout strategies such as distributed layouts that handle part mix and demand changes are used, have to be investigated. This is particularly important given the current focus on small lot sizes in agile manufacturing.

Comparison of dynamic cells (in which physical cells are reconfigured periodically) versus robust cells (in which cells stay static and uncertainties are managed through strategies such as VCMS) is needed to identify the conditions under which one would be favoured over the other.

Further, we saw in the Canon example that moving cellular manufacturing reduces the use of conveyers and other material handling equipment. This is a main advantage for physically
grouped cells. However, it is conceivable that in layouts where cells are not grouped together such as distributed or holonic cells, material handling systems may still be required. Thus the equipment investment tradeoffs need to be made between pure CMS and non-physical CMS.

Another layout design issue that could be addressed in the future is that of lead times and its variability in the procurement of resources, such as equipment from suppliers, in order to redesign the layout. The longer this lead time is, the longer the forecast horizon for product demand and mix has to be in order to plan new layouts for the expected demand changes. For example if the lead time to acquire a machine is six months, it implies that one has to forecast at least six months into the future to ensure that the machine can be acquired in time for the layout redesign. If the lead time is one year, the forecast has to be made at least one year into the future. The variability in this lead time also has an effect. For example if the mean lead time is six months but the actual lead time varies between four months and eight months, to ensure that layout redesign schedules are not disrupted, one may have to forecast up to eight months ahead, in effect adding a safety time buffer. Forecasts further out have greater uncertainty. Thus this lead time will have an effect on the accuracy of the layout redesign plans.

5.0 CONCLUSION

There has been much literature in the area of cellular manufacturing. Most of the research in this area assume that cells once designed need not be redesigned for a considerable length of time. However, with the advent of global competition and advancements in technology, life cycles of products have become much shorter. As well, the greater desire for customized products has
resulted in the unpredictability in the volume and mix of the products that need to be manufactured in these CMS.

Some recent work in CMS has started to address cell reconfiguration and uncertainty issues. In this paper we have presented the basic problems in cell reconfiguration and uncertainty. Then we briefly described the research and have organized it into categories. The categorization also includes a summary. As seen, there have been a variety of innovative strategies and techniques used in addressing these issues. The most popular innovative approach to CMS appears to be virtual cells. Other methods include fractal cells and holonic cells. Solutions make use of mathematical programming, simulation and, queueing theory as well as specialized cell formation algorithms. As well there has been extensive studies by the different authors on the conditions under which proposed strategies and techniques have been useful. Finally we also identify some future areas for research.

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## APPENDIX

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