DYNAMIC CELLULAR MANUFACTURING UNDER MULTIPERIOD PLANNING HORIZONS

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Abstract

In this research paper cellular manufacturing is discussed under conditions of changing product demand. Traditional cell formation procedures ignore any changes in demand over time from product redesign and other factors. However given that in today's business environment, product life cycles are short, a framework is proposed that creates a multi-period cellular layout plan including cell redesign where appropriate. The framework is illustrated using a two stage procedure based on the generalized machine assignment problem and dynamic programming. This framework is conceptually compared to virtual cell manufacturing, which is useful when there is uncertainty in demand rather than anticipated changes in demand. A case study is used to explain how the concept would work in practice. One major characteristic of the proposed method is that it is flexible enough to incorporate existing cell formation procedures. It is shown through an example problem that the proposed two stage method is better than undergoing ad hoc layout changes or ignoring the demand changes when shifting or cell rearrangement costs exist. It also sheds some insight into cellular manufacturing under dynamic conditions. Thus this paper should be useful to both researchers and practitioners who deal with demand changes in cellular manufacturing.

Keywords: Cellular Manufacturing, flexibility, facility layout, dynamic cells, virtual cells, dynamic programming

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1.0 INTRODUCTION

In order to be successful in today's competitive manufacturing environment managers have had to look at new approaches to facilities planning. It is estimated that over $250 billion is spent in the United States alone on facilities planning and re-planning (Tompkins et al., 2003, p10). Thus effective layout planning can yield considerable benefits. One such approach or philosophy is called Group Technology (GT). GT is based on the principle of grouping similar parts into families. This paper focuses on cellular manufacturing (CM), an important aspect of GT. CM concentrates on the formation of groups of machines (cells) that process one or more part-families. Various approaches have been suggested for forming manufacturing cells. However, most of these methods assume that the demand stays constant over long periods of time. But in today's market based and dynamic environment, such demands can change quickly. For example, 75% of Hewlett Packard’s (HP) revenues are from product models are less than three years old and this percentage is increasing (Hammer, 1996, p212). In fact HP now uses specialized forecasting methods for it short life cycle products since traditional forecasting methods are no longer sufficient (Burruss and Kuettner, 2003). Thus when manufacturing cells are created, expected changes in products have to be kept in mind. Dynamic layout research deals with designing layouts when product demands change over time. In this research we combine cellular manufacturing research and dynamic layout research to model manufacturing cell formation under dynamic demand.

Rosenblatt (1986) discusses dynamic layout. Good discussions of GT 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.

2.0 PREVIOUS WORK

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 common machines are then physically grouped together and dedicated to producing these part-families. Cells combine the advantages of flow shops and process layouts such as reduced cycle times compared to jobs shops and increased flexibility and greater job satisfaction as compared to flow shops. There are some disadvantages however. Machines utilization may be lower due to dedication. Also much training is required in order to operate cells effectively.

Most cell formation procedures described in Selim et al. assume that once the cell is formed, the machines will not be moved for a long time. However in many instances, product demand may change quickly, rendering the current cell obsolete. Thus, depending on the demand, the cellular configurations would have to change over time. We call this problem the dynamic cellular manufacturing problem.

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. Similarly new parts are allocated to existing cells. So cells were not rearranged in their multi-period design. Harlahakis et al. (1994) also consider product demand changes during a multi-period planning horizon. Their design is based on robustness, i.e., designing a cellular configuration that would be effective over the ranges of expected demand over multiple periods. Thus once the cells are designed they are expected to remain unchanged during the multi-period horizon. Similarly Seifoddini (1990) has incorporated probabilistic demand in designing static cells. 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 were 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.

We suggest an alternate framework. We propose changing the cellular configuration periodically when the cost-benefit analysis favours such a move. In this way, the cellular layout will be better suited to the demand in each period and thus be more effective and agile during the planning horizon. In addition we propose examining multiple layouts when considering cell redesign in order to incorporate different qualitative and quantitative considerations. Such an analysis can also highlight the need for easily movable machines to ensure that cellular manufacturing is effective throughout the planning horizon.

3.0 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 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. McLean et al. (1982) were one of the first propose such an approach. In a VCMS machines in a functionally organized facility would be temporarily dedicated to a part family. When a job is to be done 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 (1996) 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). 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 large distances within the virtual cell.

In comparing VCMS to traditional CM, Subash Babu et al. (2000) categorize CM benefits into three types: (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 setup, smaller batch sizes, increased quality, productivity, and agility. They suggest that VCMS may not offer benefits in the first category, while providing considerable advantages in the second and third categories.

Benjaafar et al. (2002) suggest that a distributed layout might help in virtual manufacturing. In a distributed layout, machines of the same type are not grouped together as in a process layout but they are distributed through out the facility individually or in clusters. 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. Drolet et al. (1989) and Drolet and Moodie (1990) discuss algorithms and scheduling in VCMS, while Drolet et al. (1996) discusses VCMS within the context of the evolution of CM. Recently 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.

Kannan and Ghosh compare VCMS to CM and process layouts by using simulation. The simulated facility consisted of forty parts and thirty machines. The CM layout consisted of five cells, while the process layout consisted of eight departments. Five different configuration rules for VCMS were considered. These included rules such as; for a machine, giving allocation priority to a family with low average slack per job , or to a family with the fewest remaining machines needed to complete a cell. Inter-family setup times were higher than intra-family setups as is common in practice. The demand pattern had variability (uncertainty) through part mix changes. Primary performance measures included mean flow time, mean tardiness and the mean and standard deviation of the work in process (WIP).

The results showed that the VCMS outperformed both the process layout and CM over a wide range of conditions. When there was less demand uncertainty, the cellular advantages of VCMS were utilized, while when demand uncertainty was high, the VCMS' ability to quickly reconfigure the cells were utilized. The simulation showed that VCMS allowed jobs to spend less time in queues and setup as compared to process layouts due to dedicated routings and shared family setup. While the VCMS expectedly outperformed cellular manufacturing when setup time was low and demand uncertainty was high (conditions under which CM is not very desirable), the VCMS also outperformed CM when setup time was high and demand uncertainty was low (conditions under which CM has shown to be useful). This was due to the fact that the VCMS had the ability to exploit production similarities while not giving up any flexibility. It was also shown that some of the VCM rules performed poorer than the others. Kannan (1997) further investigates the effect of family configuration on VCMS performance.

Prince and Kay (2003) discuss the use of virtual groups (VG) to enhance agility and leanness in production. Both VCMS and VG uses 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. Group managers would be assigned a team of operators and all the machines required to make complete products or major subassemblies. Thus 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 a VCMS different machines in a group could be managed by different groups, thus not utilizing the advantage of teams. Thus VGs are an attempt to improve upon some of the disadvantage of VCMS.

While VCMS have advantages over CM, it can result in not being able to use the human related factors as stated by Subash Babu et al. Human factor advantages are difficult to evaluate through computer simulations such as in Kannan and Ghosh, thus sometimes tending to be overlooked. Important human factors aspects of CM 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 CM. Outside each cell is posted a board where performance indicators such has lead times, WIP, and bottleneck measures are posted. Thus any deterioration in performance can quickly be identified and corrective measures taken. In a VCMS or VG where machines are not grouped together, such 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 CM, the team managing the cell would responsible for the performance.

HP (Hewlett-Packard, 1984) is another example of a company that uses CM 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.

In addition as mentioned before, VCMS and VG may not improve travel times compared to a process layout since the machines in a cell may be located far away from each other. Thus it is important as far as possible to maintain a physical grouping of machines. Dynamic cellular manufacturing is a concept which allows for the physical grouping of cells while allowing cell rearrangement periodically in appropriate situations.

4.0 DYNAMIC MANUFACTURING CELLS

4.1 The dynamic manufacturing cell model

Dynamic manufacturing cells are useful when there are anticipated changes in product demand due to new products. Demand may be said to be dynamic in this situation. For example, one of the authors is familiar with a company that manufactures pressure vessels under contract (including fuel tanks for military aircraft) for a variety of clients. Since these are made under contract the company can forecast the future flow of material quite accurately depending on when they will be starting to work on a particular contracted job. Under such a situation is it is advantageous to consider grouping cells physically together and then rearranging them if the material flows changes under a new contract. This will allow them to take complete advantage of CM as well as retain the flexibility through reconfiguring cells on a planned basis.

An example of a four period dynamic cellular manufacturing problem is shown in Figure 1. Let X be the optimal cellular configuration of the layout in period 1. 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 was 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 cellular system within the multi-period horizon. But rearranging cells has associated costs such as moving machines, lost production time, and re-learning. Thus the decision to rearrange should be taken only after a cost benefit analysis. Further, using a wrong cellular configuration in a period could result in excess shifting costs in subsequent periods. Thus there are two types of conflicting costs and the objective determining a dynamic or multi-period cellular configuration plan is to minimize the sum of these over the planning horizon. Due to rearrangement 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 shifting and lower 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 sub-optimal cellular configurations can be used in each period, we have to include every possible cellular configuration in order to ensure overall optimality.

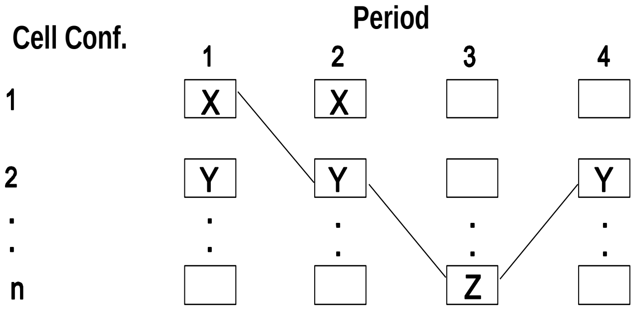

Figure 1: The Dynamic Cellular Manufacturing Model

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 our cells will become outdated quickly resulting in excess costs.

4.2 An example of the applicability of the model

da Silveira (1999) describes a toy manufacturer where the proposed analysis might be applicable. The manufacturer initially used a functional layout to manufacture a wide variety of toys. As the company grew, management was having problems with the functional layout. This led to deterioration in cost, quality, speed and dependability. Management realized that the process had to be improved.

They evaluated the possibility of installing programmable technologies but decided against since it would involve resources and skills that they did not have. In addition it was felt that automation might alienate the employees. Besides it was felt that any solution would have to involve the workforce so they would be actually part of the improvement process and benefit from it.

As a result the company management decided to implement CM. The paper discusses a pilot implementation in the woodworking section of the company. The cell formation itself was done using a clustering algorithm and inter-cell flow was kept to a minimum. A series of meetings were conducted with employees to ensure commitment to the improvement process and to involve them in the implementation of the redesign. The actual movement of equipment and people into the new cells took about one week. A group of employees simulated assembly activities to regulate the production flow, and to make some final adjustment in the layout and in the organization. The cells used kanban type scheduling. An analysis of the results showed that there was significant improvement in delivery time, WIP inventory levels, rework, space requirements and delays. There was more worker autonomy in the cellular structure. Further the cellular layout also improved health and safety.

Many of the these improvements probably would not have beeen obtained using a VCMS, since advantages such as empowerment and shorter transportation times depend on the equipment in the call being physically close.

The toy company was constantly developing new products to explore new market trends or niches. Even during the implementation, the cell structure had to be changed since the new products were introduced . However for an introduced product the demand was fairly stable with predictable seasonality (da Silvera, 2004). Further da Silveira (1999) states that the machines used in the woodworking section were mobile. Thus it appears to have been a situation where planning based on the expected introduction of new products would have been beneficial. Given that it took a week to reconfigure the entire layout for the woodworking department, it is important not to do this on an ad hoc basis. Even if future cell reconfigurations may be less major, there would be a significant cost in moving machines and lost production. Thus these reconfigurations should be done as required based on a strategic multiperiod cell configuration plan that trades off the benefits of rearranging the cells against the costs of such reconfigurations. With stable demand one can be confident that a multiperiod plan could be adhered to and the amount of variation is demand would not be sufficient to warrant unanticipated cell reconfigurations.

Such a strategic plan would be quite useful in what-if analysis. For example in the toy factory, a dynamic cellular manufacturing plan would involve designing cells for the initial period and then determining what if any changes to make in the future based on the planned new product development. In the first stage of the two stage procedure described in the next section, the cells could be designed robustly at the first stage, such that there would be minimal changes in the future since the robust layout might satisfy requirements in future periods also. This could be a good option if cell configuration rearrangement costs, such as the lost production and the cost of moving equipment were relatively high. However, robust layouts can also imply that its is a satisficing solution in any specific period, i.e, there a may be better configurations for that period. Thus the proposed model includes multiple designs to choose from in any period. So a less robust design from a multiperiod perspective, but one that is better with respect to a single period could be chosen if the rearrangements costs were low since it would be better to change from a good cell configuration in one period to another good one in the next period rather than stay with the same robust cell configuration that might not be as good in either period. The second phase of the model chooses one cell configuration for each period given the single period cell configurations. An example numerical problem is presented in a later section.

Another way in which dynamic cell configuration could help is by identifying the equipment where the company might make improvements in the mobility of the equipment. For example in the toy factory there were machines that were too huge to move. This of course would hamper call configuration. If the dynamic cell configurations analysis shows that some machines are not being moved because of high shifting cost and in addition these high costs are resulting in poor cellular configurations, the company can work on reducing the cost of moving these machines or replacing the machines by alternatives with better mobility so that better cells in each period can be utilized. This will increase the agility of the process. Thus it provides a process improvement focus based on multi-period planned changes in product flow. The next section describes the proposed two stage approach that can incorporate demand changes.

5.0 THE PROPOSED TWO STAGE PROCEDURE

5.1 Stage 1 - Solving the static (single period) phase

This phase involves solving the machine assignment problem. As mentioned in the previous section, in order to obtain an optimum solution for the problem, all the possible cellular configurations in each period would have to be evaluated. This would correspond to the *n* configurations shown in Figure 1. However for most practical sized problems, this would be computationally prohibitive as shown in Table 1 for a seven machine problem assuming that a cell has to contain at least two machines.

Cell Configuration	Number of Machines per Cell			Combinations Possible	Number of Combinations
	Cell 1	Cell 2	Cell 3		
1	2	5		${}_7C_2 \times {}_5C_5$	21
2	2	3	2	${}_7C_2 \times {}_5C_3 \times {}_2C_2$	210
3	3	4		${}_7C_3 \times {}_4C_4$	35
				Total	**266**

Table 1: Possible configurations for a seven-machine problem.

There would be n = 266 different cellular configuration possibilities in each period. For a five period problem there would be 266^5 or 1.33×10^{12} possibilities in the dynamic (multi-period) phase. This is a huge number given the small number of machines. Thus most practical sized problems will have to be solved heuristically by including a sample of the cellular configurations possible in each period. The static phase of the framework involves identifying the appropriate cellular configurations from each period that will be included in the dynamic phase of the problem. Since this phase is independent of the second phase, any appropriate method can be used. Thus the proposed procedure is very flexible.

The simplest method to generate static cellular configurations would be to do it randomly. In this method, given different cell sizes, the machines would be assigned randomly to each cell. This would give some of the possible cellular configurations. However, research by Rosenblatt showed that this was not effective. When only s configurations, where $s < n$, can be included due to computation time restrictions, a good alternative according to Rosenblatt is to include the best s cellular configurations instead of generating the s configurations randomly. Alternately if finding the best s combinations is also time prohibitive, s good cellular configurations could be used. If a method with high computation time is used, only a few configurations will be generated. Similarly, if the cellular configurations are created manually using qualitative considerations, only a few configurations may be created. If the algorithm used is quick then many configurations can be generated. A combination of manual and algorithmic solutions can also be used.

5.2 Stage 2 - Solving the Dynamic Phase

From Figure 1, it can be seen that the dynamic cellular manufacturing problem lends itself quite well to dynamic programming (DP). The objective of dynamic cellular manufacturing is to arrive at the best multi-period plan. In order to do this we have to determine the best cellular configuration (state) in each period (stage). The total cost of the plan will minimize the sum of the shifting and material handling costs within the plan horizon. The procedure used is a DP algorithm based on Rosenblatt

Let

L_i	*Cellular configuration i*
A_{ij}	*Rearrangement (sum of shifting costs) cost when changing from cellular configuration* L_i *to cellular configuration* L_j*. This cost is independent of the period in which it occurs.*
F_{it}	*Material handling cost for cellular configuration* L_i *in period t. This is obtained from the Stage 1 solution.*
C^*_{it}	*Minimum total costs (material handling and shifting) for all periods up to t where* L_i *is used in period t.*

The combination of cellular configurations with the minimum total cost is chosen based on the following recursive relationship:

$$C^*_{jt} = Min_i \{C^{*i}_{i(t-1)} + A_{ij}\} + F_{jt} \tag{1}$$

The DP is solved using backward recursion. Each period in the planning horizon forms a stage and each cellular configuration from Stage 1 forms a state. The two stage algorithm is applied in the illustration in the next section.

6.0 ILLUSTRATIVE PROBLEM

The facility consists of 18 machines and 10 parts. Each part's routing in general includes more that one machine (not shown). We assume five periods and changes in part requirement over each period as in Table 2. It is seen that the demand is dynamic. For example part 5 has the highest demand of all the parts in period 1, while in period 2, it is part 7 that experiences the highest demand. In practice a part may be discontinued and a new part substituted in its place. This places varying loads on the different machines in different periods. Given the routing and processing requirement of ten parts (not shown) on the eighteen machines during each of the 5 periods, the material flows between the different machines were determined in each of the five periods (not shown).

Parts										
Demand	1	2	3	4	5	6	7	8	9	10
Period I	423	241	423	324	537	352	314	292	324	399
Period II	173	341	403	324	337	319	414	392	324	319
Period III	573	241	103	394	137	419	214	192	394	219
Period IV	215	341	193	314	337	479	414	492	394	342
Period V	395	341	393	314	337	179	434	451	294	342

Table 2: Multi-period part demand

To create cells, the algorithm of Cheng et al. (1996) based on the generalized machine assignment problem was used. Different cellular configurations to be included in the dynamic phase are generated by changing the limits on the number of machines per cell that will result in different cellular configurations for each period. Figure 2 shows two solutions obtained by using the algorithm. These might correspond to configurations X and Y in Figure 1. A ‘1’ indicates that the machine is assigned to that cell. Since any method including manual methods could be used, we can use any cell formation method that incorporates our considerations appropriately such as ensuring that a product family remains in one cell etc. All that is required is that we have multiple solutions.

Solution 1

Machines

Cells	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0	0	1	0	0	0	1	1	0	0	0	1	0	1	0	0	0	1
2	1	0	0	1	1	1	0	0	0	1	0	0	0	0	0	1	0	0
3	0	1	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0

Solution 2

Cells	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	1	0
2	1	0	0	0	1	0	1	0	0	1	0	0	1	1	0	0	0	0
3	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	1	0	1

Figure 2: Cellular Configurations

Once the fifty cellular configurations are obtained from the static phase, the dynamic programming algorithm can be applied. From Figure 1, we see that the material handling cost (F_{it}) and the rearrangement cost between each pair of cellular configurations (A_{ij}) in the problem is needed in order to solve the problem. We assume that the cost to move a machine is fixed at $100 per move. However this assumption can be relaxed without loss of generality as explained later. The calculation or rearrangement cost can be illustrated using Figure 2. To find the total rearranging cost in shifting from Solution 1 (cellular configuration 1) to Solution 2 (cellular configuration 2), we check whether a machine has changed its cell. It is seen that Machine 2 has moved from Cell 2 to Cell 1 in this rearrangement. So a shifting cost of $100 would be incurred. If we add up all the moves we will get that total cost of rearranging cellular configuration 1 into cellular configuration 2. The material handling cost for each cellular configuration in each period is given in Table 3 and is obtained by calculating the flow of material in the cells created by the Cheng algorithm.

In Table 3, the fifty cellular configurations in each period form the fifty states in each period and the five periods form the five stages in the problem. Thus we have 250 total states. The optimal cellular configuration in each period is shown in bold and underlined. The problem is solved using equation (1) and the solution is given in Table 4. The input data for dynamic programming consists the material handling costs from Table 3 and the rearrangement costs obtained by comparing each of the fifty cellular configurations to the others (an example of which is shown in Figure 2).

In the example problem the rearrangements costs are linear with respect to the number of moves. However any function may be used. For example assume that the rearrangement costs can represented by $(a \times b^k)$ where a is the shifting cost per machine moved, b is the number of planned machine moves between a pair of cell configurations between any successive periods, and k is a constant. Further assume that $a = \$100$ (as in the example) and $k = 0.8$. In this situation if only one machine needed to be moved it would cost a total of $100, where as if five machines were moved the total rearrangement cost would only be about $360 instead of $500 as it would if the function were linear. Thus this function would model economies of scale in cell rearrangement. So Phase 2 of the model is quite general in accommodating different types of cell rearrangement costs.

Note that since we employ only fifty cellular configurations in each period, the final solution is optimal with respect 250 states in the problem. It is a heuristic solution to the overall dynamic cellular manufacturing problem. The best solution as in Table 4 (under the $100 column) is to employ cellular configuration 45 in periods 1, 2 and 3. Then the cellular configuration should be changed to configuration 6 in period 4 and remains unchanged till the end of the horizon. The total cost including shifting and material handling is $531585. If we had made our decision based on only the first period's demand and not responded to the changes in demand, we would have employed cellular configuration 45 for all five periods. This would have resulted in a higher cost of $538190 (only material handling costs and no shifting costs). Also it is seen (in Table 3) that optimal static cellular configurations are 45, 33, 45, 4 and 6 in periods 1 through 5 respectively. Thus the optimal multi-period solution does not employ all the static optimal configurations due to the presence of rearrangement costs. Had we used a policy of changing to the single period optimal configuration at the end of each period (no advance planning), our cost would have been $539520, higher than that for the dynamic plan. This shows that it is important incorporate the cost of cellular rearrangement in our cellular layout plan.

Table 4 also illustrates the managerial implications of not being flexible. When the shifting cost increases to $500, the same cellular configuration, 45, is employed in all the periods. However, configuration 45 is not optimal in all the periods 1 and 2. Thus due to the high shifting costs, we are using cellular configurations that are actually ineffective. When the shifting cost is very low, ie $10 (we use a very low value to illustrate the importance of reducing rearrangement cost by measures such as employing easily movable machinery with wheels, Hirano (1989)), we see that the configuration changes every period. In addition, from Table 3, we can also see that configurations 6, 4, 45, 33, and 45 are the optimal configurations in periods 1, 2, 3, 4 and 5 respectively. Thus when shifting costs are really low, we can always use the best cellular configurations and enjoy maximum cell effectiveness and agility. So, one of the requirements of successful cellular operation under changing demand is that rearrangement costs be low. If the rearrangement costs are high, a process type layout or VCMS might be preferable. In our problem, when the rearrangement costs are $500, we are in effect using inefficient cellular configuration in some periods. In an inefficient cellular configuration, there would be significant part movement between cells. This would negate some of the benefits of cellular manufacturing. Thus it might be better just to have a process layout or VCMS and not consider cellular manufacturing since the alternatives might provide better flexibility. On the other hand, if we can achieve low shifting costs then we can accrue the benefits of cellular manufacturing without having to live with some of the disadvantages when product demand changes.

The analysis can also identify machines that need to be made easily movable. For example, if a machine needs to be moved often during the multi-period plan, it may be a candidate for improving its mobility. Similarly if an analysis of the multi-period plan identifies a machine that should be moved in order to make cells more effective but is not being shifted because of high shifting costs, this machine may be another candidate for mobility improvement.

In our example the costs included only those of material handling and shifting. But the approach can include other types of costs also. For example, if the company is able to determine cycle times for various cellular configurations and the costs of the different cycle times, these costs can be added to the costs of material handling to determine the total cost for a cellular configuration. In fact the higher the costs of the cellular configuration relative to the cost of shifting, the more we would rearrange to get a better cellular configuration in each period since the opportunity costs of not doing so in terms of material handling, slower cycle time, etc are that much higher.

Solution (cellular configuration)	Period				
	1	2	3	4	5
1	132480.0	120810.0	122660.0	104300.0	98650.0
2	133785.0	123410.0	126745.0	106290.0	101310.0
3	126775.0	118100.0	119395.0	107570.0	99555.0
4	128935.0	120230.0	116710.0	**99865.0**	95010.0
5	123460.0	113825.0	115140.0	102730.0	96000.0
6	124735.0	115980.0	116285.0	100295.0	**93960.0**
7	197670.0	186630.0	183620.0	164890.0	155330.0
8	170775.0	165210.0	157220.0	151960.0	149315.0
9	189405.0	178650.0	173075.0	165760.0	156950.0
10	190305.0	184635.0	183800.0	178615.0	170480.0
11	130215.0	122825.0	124045.0	108720.0	100510.0
12	134715.0	125820.0	122785.0	106175.0	99695.0
13	123015.0	116660.0	113940.0	102870.0	96715.0
14	127450.0	119325.0	118565.0	104645.0	97590.0
15	117430.0	113640.0	111440.0	101545.0	94925.0
16	123615.0	116760.0	116645.0	103600.0	98270.0
17	197670.0	186630.0	183620.0	164890.0	155330.0
18	182040.0	167775.0	169445.0	154735.0	152795.0
19	184965.0	176505.0	173720.0	154240.0	144440.0
20	197550.0	182220.0	182960.0	169855.0	163355.0
21	131430.0	121075.0	122995.0	109175.0	103050.0
22	126855.0	119150.0	126415.0	113820.0	103535.0
23	122740.0	114745.0	117485.0	105340.0	96835.0
24	129390.0	120405.0	122940.0	106560.0	96975.0
25	119165.0	110590.0	113725.0	102230.0	97560.0
26	125615.0	113495.0	120820.0	105095.0	95830.0
27	205335.0	188955.0	195470.0	165970.0	157175.0
28	180510.0	173040.0	165080.0	155185.0	147485.0
29	192210.0	183930.0	173960.0	160570.0	157190.0
30	197475.0	186120.0	176450.0	161365.0	156650.0
31	130010.0	121345.0	123675.0	109765.0	103430.0
32	123350.0	116900.0	120255.0	114155.0	104885.0
33	115145.0	**109075.0**	113650.0	108130.0	97980.0
34	124260.0	117345.0	122520.0	111230.0	101450.0
35	118560.0	112035.0	114775.0	105160.0	97485.0
36	114505.0	109525.0	111220.0	106985.0	98705.0
37	194580.0	187920.0	181265.0	164920.0	157775.0
38	179715.0	163350.0	163235.0	144940.0	146750.0
39	196965.0	191955.0	183065.0	161440.0	158975.0
40	197235.0	181620.0	180545.0	158095.0	156785.0
41	132430.0	125025.0	125550.0	110645.0	104240.0
42	124105.0	120135.0	122565.0	116200.0	107015.0
43	125275.0	116160.0	120420.0	109435.0	102440.0
44	121330.0	115525.0	117845.0	112230.0	104845.0
45	**114095.0**	109710.0	**110725.0**	104930.0	98730.0
46	120555.0	114580.0	114940.0	106900.0	100475.0
47	194580.0	187920.0	181265.0	164920.0	157775.0
48	193110.0	179580.0	172100.0	147610.0	142235.0
49	199725.0	189750.0	184535.0	165595.0	151280.0
50	198975.0	184560.0	186785.0	161200.0	149120.0

Table 3: Cellular configurations material handling cost

Shifting Cost Per Machine ($)						
Period	500		100		10	
	Cell Conf #.	Cumulative Cost	Cell Conf #.	Cumulative Cost	Cell Conf #.	Cumulative Cost
1	45	538190	45	531585	45	528900
2	45	424095	45	417490	33	414525
3	45	314385	45	307780	45	305170
4	45	203660	6	194255	4	194145
5	45	98730	6	93960	6	93960

Table 4: The effect of shifting costs

7.0 CONCLUSION

This paper presented a flexible framework for modelling cellular manufacturing when product demand changes during the planning horizon. This framework can incorporate various types of problem specific situations including qualitative considerations. It is conceptually compared to VCMS which is appropriate under uncertain demands. It is also important to note that using a multi-period planning horizon can shed some light on aspects of cellular manufacturing that may not be available by examining cellular manufacturing based on a one period horizon. The example used in this paper shows that as cell rearrangement costs increase, jobs shops may be preferred to cellular manufacturing. In addition, the example also shows that if one can reduce cell rearrangement costs, then cellular manufacturing will be more rewarding for the organization. Thus it illustrates that in order to make cellular manufacturing viable in a changing demand environment, reduction of layout rearrangement costs as seen in JIT organizations may be important.

REFERENCES

1. Askin, R.G., Selim H.M. and Vakharia A.J. (1997), "A methodology for designing flexible cellular manufacturing systems", *IIE Transactions*, Vol. 29, pp. 599-610.

2. Benjaafar, S. Heragu, S.S. and Irani, S.A. (2002), "Next generation factory layouts: research challenges and recent progress", *Interfaces*, Vol. 32, No. 6, pp. 58 -77.

3. Burbidge, J.L.(1963), "Production flow fnalysis", *Production Engineer,* Vol.42, pp. 742-752.

4. Burruss, J. and Kuettner, D. (2002), "Forecasting for short lived products: Hewlett Packard's journey", *Journal of Business Forecasting*, Vol. 21, No. 4, pp 9-14.

5. Cheng, C.H., Goh, C-H, and Lee, A. (1996), "Solving the generalized machine assignment problem in group technology", *Journal of the Operational Research Society*, Vol. 47, pp.794-802.

6. da Silveira, G. (1999), " A methodology of implementation of cellular manufacturing", *International Journal of Production Research*, Vol. 37, No. 2, pp. 467-479.

7. da Silveira, G. (2004), Personal communication

8. Drolet, J., Moodie, C. and Montreuil, B. (1989), "Scheduling factories of the future", *Journal of Mechanical Working Technology*, Vol. 20, pp. 183-194.

9. Drolet, J. and Moodie, C. (1990), "A virtual cell scheduling algorithm", *Progress in Materials Handling and Logistics*, Vol. 2, Springer-Verlag, pp. 489-500.

10. Drolet, J., Abdulnour, G. and Rheault, M. (1996), "The cellular manufacturing evolution", *Computers and Industrial Engineering*, Vol. 31 No. 1/2, pp. 139-42.

11. Hammer M. (1996), *Beyond Reengineering*, New York, NY: HarperCollins, p 212

12. Harlahakis, G., Ioannou, G., Minis, I, and Nagi, R. (1994), "Manufacturing cell formation under random product demand", *International Journal of Production Research,* Vol. 32, No.1 pp 47-64.

13. Hewlett-Packard Company (1984), "Stockless production", *HP-TV Network*, 1891 Page Mill Rd., Palo Alto, CA 94304.

14. Hirano, H.(1989), *JIT Factory Revolution,* Cambridge MA: Productivity Press,

15. Kannan, V.R. and Ghosh, S. (1996), "A virtual cellular manufacturing approach to batch production", *Decision Sciences*, Vol. 27, No. 3, pp. 519-39.

16. Kannan V.R. (1997), "A simulation analysis of the impact of family configuration on virtual cellular manufacturing", *Production Planning and Control,* Vol. 8, No. 1, pp 14-24.

17. McLean, C.R., Bloom, H.M. and Hopp, T.H. (1982), "The virtual manufacturing cell", *Proceedings of the 4th IFAC/IFIP Conference on Information Control Problems in Manufacturing Technology,* Gaithersburg, MD, USA, pp 1-9.

18. Prince, J. and Kay, J.M. (2003), "Combining lean and agile characteristics: creation of virtual groups by enhanced production flow analysis", *International Journal of Production Economics*, Vol. 85, pp 305-318.

19. Ratchev, S.M., (2001) "Concurrent process and facility prototyping for formation of virtual manufacturing cells" *Integrated Manufacturing Systems*, Vol. 12, No. 4, pp 306-315.

20. Rosenblatt M.J. (1986), "The dynamics of plant layout", *Management Science*, Vol. 32, No. 1, pp. 76-86.

21. Seifoddini, H., "A probabilistic model for machine cell formation", *Journal of Manufacturing Systems*, 9, 1, 1990, 69-75.

22. Subash Babu, A., Nandurkar, K.N. and Thomas, A. (2000), "Development of virtual cellular manufacturing systems for SMEs", *Logistics Information Management,* Vol. 13, No. 4, pp 228-243.

23. Selim, H.M., Askin, R.G., and Vakharia A.J.(1998), "Cell formation in group technology: review, evaluation and directions for future research", *Computers and Industrial Engineering*, Vol. 34, No. 1, pp. 3-20.

24. Suresh, N.C., and Meredith J.R. (1985), "Achieving factory automation principles through group technology principles", *Journal of Operations Management*, Vol. 5, No. 2, pp.151-167.

25. Tompkins, J.A, White ,J.A., Bozer, Y.A., and Tanchoco J.M.A. (2003), *Facilities Planning,* New York: Wiley.

26. Vakharia A.J., and Kaku B.K (1993)., "Redesigning a cellular manufacturing system to handle long-term demand changes: a methodology and investigation", *Decision Sciences*, Vol. 24, No.5, pp. 909-929.