Analyzing the Tradeoff Between Efficiency and Flexibility in Cellular Manufacturing Systems

Vijay R. Kannan
College of Business
James Madison University
Harrisonburg, VA 22807.

Phone: (540) 568 3053
Fax: (540) 568 3273
Email: kannanvr@jmu.edu

Analyzing the Tradeoff Between Efficiency and Flexibility in Cellular Manufacturing Systems

ABSTRACT

A limitation of Group Technology (GT) based cellular manufacturing systems is that their limited routing flexibility offsets the setup and material handling efficiencies they offer. Virtual Cellular Manufacturing (VCM) systems do not encounter the problem of limited routing flexibility but do not yield the same efficiencies as GT based cellular systems. This study compares the performance of a GT based cellular manufacturing system that utilizes operations overlapping to further improve material flow efficiency with that of a virtual cellular manufacturing system. Results suggest that while the use of operations overlapping in a GT based cellular manufacturing system can to some extent compensate for the system's low routing flexibility, it cannot fully overcome the high flow time variance that results from the permanent dedication of machine resources. As a result, GT based cellular manufacturing performs comparably to VCM only under a limited set of conditions.

Keywords: Cellular Manufacturing, Group Technology, Simulation

1. Introduction

Several studies have highlighted a significant limitation of Group Technology (GT) based or physically configured cellular manufacturing systems, namely that by dedicating machine resources to specific product families, routing flexibility is compromised (e.g., Flynn and Jacobs 1987, Morris and Tersine 1990, Suresh 1992, Suresh and Meredith 1994). This is attributable to what Suresh & Meredith term the loss of pooling synergy associated with partitioning shared resources into dedicated cells. The result is that despite the inherent advantages of cellular shops, in particular the setup and material handling efficiencies they offer, their performance is considerably poorer in comparison to job shops. In contrast, cells in Virtual Cellular Manufacturing (VCM) Systems (Kannan and Ghosh 1996) are not physical structures but logical structures created by scheduling jobs in a job shop using family based scheduling mechanisms. By defining cells in this way, routing flexibility is not compromised yet some of the setup efficiencies of GT based cells are retained. VCM was shown to yield significantly better throughput, work in process and due date performance over a range of operating conditions than either a job shop or a GT based cellular manufacturing system. In addition, VCM was shown to be less sensitive to increases in shop load and variability in demand patterns than GT based cellular systems.

From the perspective of material flow, VCM systems remain constrained by the fact that physically they resemble a job shop. The proximity of machines, simplified flow patterns, and reduced complexity in production scheduling and control observed in GT based systems, are not observed in VCM systems. The physical configuration of GT based manufacturing cells however provides opportunities to further improve the efficiency of material flow and potentially offset the reduced routing flexibility observed in these cells. One particular mechanism to accomplish this is operations overlapping. The proximity of machines in a GT based cell makes it feasible to transfer jobs between machines in transfer batches that are a fraction of the job size. Morris and Tersine (1989) showed that when job arrival rates are low, the performance of a manufacturing cell improves if only a single job is processed within a cell at a time and unit size transfer batches are used. At higher arrival rates, utilization rates fall and performance deteriorates. Sassani (1990) demonstrated a similar improvement in cellular shop performance when transfer batch sizes are reduced. Shafer and Charnes (1993) showed that when unit size transfer batches are used, GT based cellular systems can offset their limited routing flexibility and in fact yield lower values for mean flow time and work in process than job shops over a range of conditions. However, their study was carried out at low levels of shop load and did not examine the impact of operations overlapping on flow time variance or due date performance.

While the limited evidence suggests that VCM may be a more effective means of batch manufacturing than GT based systems, a 'fair' comparison of the two has not to date been carried out. In other words, VCM has not been compared with a GT based cellular manufacturing system that was implemented in a way that takes advantage of its material handling efficiencies, i.e., using operations overlapping. The objective of the current study is to fill this void in the literature, examining the question of whether routing flexibility or setup/material handling efficiency has a greater impact on the performance of batch manufacturing systems, and how this is affected by shop load. The implications are significant. While converting a job shop to a GT based cellular shop is an option for companies seeking to improve manufacturing efficiency, it requires significant investment to accomplish. Moreover, given the cost and time required to physically reconfigure a shop, frequent reconfiguration is impractical and in many cases, infeasible. As product life cycles shrink and product variety increases, companies may not be willing to forego the flexibility of a functionally organized shop unless the efficiencies of GT based cellular shops can be expected to justify doing so.

2. Virtual Cellular Manufacturing

Virtual cellular manufacturing (Kannan and Ghosh 1996) is an approach to batch manufacturing that combines the routing flexibility of job shops with the setup efficiencies of group technology manufacturing cells. It is based on the premise that the underlying principle of GT based manufacturing systems, namely that similarities in part processing requirements should be recognized and exploited, can be separated from the layout element of GT based systems. This can be accomplished by using family based (group) scheduling rules to realize scheduling and setup efficiencies but doing so within a job shop. The result is that unlike the permanent, physical cells found in GT based cellular systems, temporary, virtual cells are formed that require no physical changes in shop layout. Furthermore, VCM facilitates dynamic reallocation of machine resources making it more responsive to changes in demand and shop conditions.

Different heuristics can be used to assign idle machines to families, e.g., the family with the most jobs in the current queue, or the family requiring the fewest machines to complete a cell. At any point in time, machines from different process departments will be allocated to and setup for a given part family to form a virtual rather than a physical cell. This allows some of the setup efficiencies of GT cellular manufacturing systems to be realized without compromising routing flexibility. As production requirements change, cells relinquish machines, and, over time, cells dissolve and new cells form and evolve, thus the continuous, dynamic reallocation of machines.

To ensure equitable allocation of machines and to promote development of multiple cells, virtual cell formation is governed by two additional constraints. First, priority in machine allocation is given to families that do not currently have access to a machine of the type being allocated. Second, if multiple machines of the same type are allocated to a family, they remain allocated to the family until they are no longer needed or until another family has jobs waiting to be processed on the machine type but has no machines of the type allocated to it. In the latter case, one of the machines in question is reallocated on completion of the current job.

3. Experimental Design

This study uses simulation to compare the performance of the two cellular manufacturing implementations, a virtual cellular manufacturing system (VCM) and a group technology based cellular manufacturing system (GTCM), under conditions that are likely to affect their relative performance. VCM is an eight department, thirty machine shop. Each department has either three or four identical machines. When a machine becomes available, it is assigned to the family with the most jobs in the current queue subject to the constraints described earlier. This assignment heuristic was shown to be one of the more effective heuristics for allocating machines to families in a VCM environment (Kannan and Ghosh 1996). In GTCM, the thirty machines are allocated to five cells with no more than one machine of the same type in any cell. Cells contain between four and eight machines. Jobs are processed entirely within a single cell and have the same routings as in VCM. Jobs are split into transfer batches on arrival at the shop. To examine the impact of transfer batch size, four transfer batch sizes are considered.

These correspond to ratios of transfer batch size to batch size of 1 (GTCM-1), 0.5 (GTCM-2), 0.25 (GTCM-3), and 0.125 (GTCM-4).

In addition to the shop configurations, three additional experimental factors are included in the simulation experiment, shop load, batch size, and major setup time. Kannan and Ghosh (1996) showed that load has a significant impact on the performance of both GTCM and VCM shop configurations but that VCM is less sensitive to increases in shop load. Both Shafer and Charnes (1993) and Morris and Tersine (1990) showed that the performance of a GT based cellular shop can be improved considerably by using operations overlapping but did not examine how this was affected by shop load. Two levels of load are investigated in this study. At the low level, mean shop load is 65%, similar to that used by Shafer and Charnes. At the high level, load is 75% similar, to the load used in Kannan and Ghosh (1996).

Previous studies have shown that as batch size is reduced, increased setup frequency can result in shop congestion and consequently poor shop performance. Kannan and Ghosh (1996) indicated (at a shop load of 75%) that even with reductions in batch size, GT based cellular systems perform poorly compared to VCM. However, by virtue of the fact that they do not incur time consuming major (inter family) setups, GT based systems should have an advantage over VCM as batch size is reduced. This advantage may be realized when the shop is less congested. Two levels of the batch size factor are considered: large batches contain 120 units and small batches contain 40 units.

The last factor, major setup time is included to evaluate the impact of setup time on the performance of the two shops. High setup time will have a greater effect on VCM systems since they incur major as well as minor (intra family) setups. Two levels of this factor are included, at the high level, major setup time is 22.66 minutes and at the low level, it is 11.33 minutes (Kannan and Ghosh 1996). Minor setup time is one quarter of the major setup time.

4. Shop Environment

The shop environment modeled in this study is the same as that used in Kannan and Ghosh (1996). Forty different parts are processed within the shops. Parts belong to one of five part families, each family containing between six and ten different parts. Jobs arrive according to a Poisson process with exponentially distributed inter-arrival times. There is an equal probability that jobs are for a particular part. Jobs are subject to between two and six operations with a mean of 3.72 operations per job. No more than one operation takes place on a given machine type. Processing time is normally distributed with mean 34.33 minutes and standard deviation 3.433 minutes for a batch of one hundred units. Due dates are set using the total work content method (Baker 1984) with an allowance of k = 3. In shop configuration VCM, jobs move between machines at a rate of five miles per hour. Since the layout of GTCM is designed to minimize distances between machines, material handling time in this shop is assumed to be insignificant. Loading and unloading times in both shops are uniformly distributed in the interval (1,5) minutes. Jobs are dispatched using the Repetitive Lots rule (Jacobs and Bragg 1988). By giving priority to transfer batches requiring the current machine setup before invoking a first come first served policy, the Repetitive Lots dispatching rule compensates for the increased setup frequency that occurs when batches in a manufacturing cell are split to improve material flow. This increase in setup frequency, if not addressed, can more than offset any advantages of small transfer batches and cause deterioration in performance (Karmarkar et al. 1985).

For each of the forty treatments (5 * 2 * 2 * 2), thirty-one replications were carried out, each consisting of two thousand jobs. In each case the first replication was deleted to control for initialization bias. Common random numbers were used for all but one input process to reduce variance while maintaining batch independence (Mihram 1974). Data was collected for three performance measures, the mean and standard deviation of flow time (σ_{FT}), and mean tardiness. The simulation model was written in SIMAN (Pegden 1987) and FORTRAN.

5. Results

Analysis of Variance showed that for each performance measure, most if not all main and interaction effects were significant ($\alpha = 0.05$). To examine the impact of these effects, Tukey multiple comparisons of means were carried out. To facilitate interpretation of results, comparisons were carried out separately for each level of shop load. Treatment means for each shop configuration were then compared for all batch size/setup time scenarios (Table 1).

5.1 Shop Load = 65%

When shop load is low, the use of operations overlapping in GTCM gives the shop the expected advantage over VCM with respect to mean flow time performance. Regardless of batch size, splitting batches in GTCM into at least four transfer batches (GTCM-3, GTCM-4) consistently results in better performance than that obtained by VCM (Figure 1). Furthermore, transfer batch size and performance are negatively correlated. Figure 1 indicates that further reductions in transfer batch size may yield additional reductions in mean flow time in GTCM particularly when batch size is large. When batch size is forty, splitting batches into only two transfer batches (GTCM-2) is sufficient to result in GTCM outperforming VCM. It should however be noted that when setup time is high and batch size is small, GTCM outperforms VCM even when operations overlapping is not used (GTCM-1).

While the use of operations overlapping allows GTCM to compare favorably with VCM with respect to mean flow time performance, the same is not true for σ_{FT} (Figure 2). When batch size is large, VCM yields values for σ_{FT} that are at least 47.5% (low setup time) or 37% (high setup time) lower than those yielded by GTCM (Figure 3). These differences are statistically significant. As expected, the advantages of VCM are less pronounced when batch size is small. Under low setup time conditions, VCM yields σ_{FT} that is at least 28% lower than that yielded by GTCM. When setup time is high, the performance of VCM is statistically indistinguishable from that of GTCM-2, GTCM-3, and GTCM-4. It is interesting to note that as long as operations overlapping is used in GTCM, there is no statistically significant impact on σ_{FT} attributable to transfer batch size. This suggests that further reductions in transfer batch size in GTCM are unlikely to reduce flow time variance and may in fact increase variance due to increased setup frequency and the consequent build up of queues.

Not surprisingly, high flow time variance in GTCM translates to poorer due date performance than in VCM. With the exception of the small batch size, high setup time scenario, VCM always yields the best due date performance (Figure 4). For this one exception, VCM yields the lowest mean tardiness but the value is statistically similar to that yielded by GTCM-3. Although in absolute terms, mean tardiness values for the GTCM shop are not large, they are statistically greater than those observed for the VCM shop. Once again, it can be observed that the performance of GTCM improves as transfer batch size is reduced. However, as Figure 4 shows, further reductions in transfer batch size may not allow the GTCM shop to better VCM.

5.2 Shop Load = 75%

When shop load is increased, the advantages of the VCM shop's greater routing flexibility are even more apparent. When batches are large, VCM consistently outperforms GTCM by a significant margin despite the use of operations overlapping. VCM yields mean flow time that is at least 34% (low setup time) or 23% (high setup time) lower than yielded by GTCM (Figure 1). Although the performance of GTCM improves as transfer batch size decreases, additional reductions in transfer batch size may not result in much additional reduction in mean flow time. Indeed, there is no statistically significant difference in mean flow time between GTCM-3 and GTCM-4. Results for σ_{FT} are even more resounding. VCM yields values of σ_{FT} that are a minimum of 76% or 66% lower than the values GTCM yields when setup time is low or high respectively (Figures 2 and 3). This in turn translates to considerably better due date performance than in GTCM (Figure 4). There is no consistent relationship between transfer batch size and either σ_{FT} or mean tardiness in GTCM and although the lowest value for σ_{FT} is obtained when operations overlapping is used, there is no statistically significant difference compared with the value obtained when operations overlapping is not used.

Similar to the case when shop load was low, GTCM fairs relatively better when batch size is small but even then, it cannot consistently outperform VCM. When setup time is low, mean flow time for GTCM-4, though numerically higher, is statistically equivalent to that yielded by VCM. When setup time is high, both GTCM-3 and GTCM-4 outperform VCM for mean flow time, and GTCM-2 performs comparably to VCM (Figure 1). Once again however, VCM consistently yields considerably lower values than GTCM for σ_{FT} and mean tardiness (Figures 2 and 4). VCM yields values for σ_{FT} that are at least 58% or 34% lower when setup time is low or high respectively (Figure 3). Transfer batch size again has no significant impact on the performance of GTCM though the highest values for σ_{FT} are obtained when no batch splitting takes place. Mean tardiness in GTCM is poorest when operations overlapping is not used, but as long as batch splitting takes place, there is no significant effect attributable to transfer batch size. Again the margin by which VCM outperforms GTCM is considerable, particularly when batch size is high.

6. Discussion

The results highlight a number of issues that help clarify the question of whether flexibility or efficiency has a greater impact on shop performance in the production environment being examined. The fact that the use of operations overlapping failed to allow the GT based cellular shop to consistently overcome its limited routing flexibility is significant. Despite attempts to increase efficiency of material flows in GTCM, the shop performed well compared to VCM under only two scenarios, when GTCM was not subject to significant congestion (low shop load) and when setup frequency placed the greatest constraint on VCM (small batch size, high load and setup times). Moreover, even under these conditions, operations overlapping, while reducing flow time variance and consequentially tardiness in GTCM, still yielded performance for these measures that is significantly poorer than the performance yielded by VCM. This is a direct consequence of the inability of permanent cells to respond effectively to bottlenecks and to reallocate resources accordingly.

The observation that when shop load is low GTCM with operations overlapping can yield lower mean flow time than VCM is consistent with the results obtained by Shafer and Charnes (1993) comparison of a GT based cellular shop with a traditional job shop implementation. However, VCM, by embodying the principles of GT based cellular manufacturing within a job shop, would be expected to perform at a higher level than a job shop. This is indeed the case, GTCM having a less considerable and less widespread advantage over VCM than was observed in Shafer and Charnes. The results here suggest that the favorable performance of the GT based shop in Shafer and Charnes' study may be largely attributable to the shop load under which they conducted their experiments. This is corroborated by the fact that when shop load is low, one scenario exists (small batch size, high setup time) for which the GT based shop is able to outperform VCM without having to use operations overlapping. This is contrary to past evidence which has consistently shown that in order for this outcome to occur, other steps must also be taken, for example reducing setup times in the GT based shop (Suresh 1992).

The results for σ_{FT} and mean tardiness are particularly significant given that these performance measures have not been examined in prior studies of operations overlapping in GT based manufacturing cells. Past studies (e.g., Kannan and Ghosh 1996) have shown that these are performance measures for which GT based cellular systems inherently perform poorly, due largely to their limited routing flexibility. The results here underscore this, performance on these dimensions being poor even under low load conditions.

The poor performance of GTCM in comparison to that of VCM is all the more significant given batches were dispatched using the repetitive lots dispatching rule. As suggested by Karmarkar et al., (1985), a consequence of batch splitting is increased setup frequency. The repetitive lots dispatching rule compensates for this yet GTCM still yields high flow time variance even under low shop load conditions. Reducing transfer batch size may only exacerbate problems caused by setup frequency. To illustrate this, consider the case when batch size is 40 and GTCM-4 is used so that transfer batch size is 5. When setup time is low, VCM enjoys a significant advantage over GTCM with respect to σ_{FT} even at a shop load of 65%. When setup time is high, σ_{FT} is actually higher for this transfer batch size than for a size of 10 (GTCM-3) though the difference is not statistically significant.

7. Conclusions

The results presented here support the assertion that while setup and material handling efficiency are desirable characteristics in a batch production environment, shop performance can be compromised if they are obtained at the expense of flexibility. While operations overlapping can enable a traditional cellular manufacturing system to yield good mean flow time performance, this can only occur when shop resources are utilized at low levels. Current trends of shortening product life cycles, increasing product variety, and shorter lead time requirements, place a premium on flexibility and responsiveness. This calls for the use of a manufacturing system that incorporates elements of both efficiency and flexibility as embodied in VCM.

The merits of VCM are all the more significant given that the experiments in this study were carried out in a manner that did not unduly tax the GT based shop. For example, the distribution of part demand was consistent with cell capacities. In practice, this may not always be the case. Changes in product mix may result in workload demands on some cells exceeding capacity for an extended period of time causing bottlenecks, while in other cells, there may be excess capacity. Under these circumstances, the lack of routing flexibility will further compromise the performance of the GT based shop, particularly with respect to flow time variance. Changes in the variety of parts produced will also increase the potential for imbalances in utilization. A shop with dedicated resources will also face a greater burden due to machine breakdowns. These factors call for an increase rather than a decrease in routing flexibility. If a GT based cellular shop is to compete favorably with VCM, measures will therefore have to be taken to offset these limitations, for example by incorporating greater flexibility or by increasing the productivity of the GT based shop.

REFERENCES

Baker, K.R., 1984, Sequencing and Due Date Assignments in a Job Shop. *Management Science*, **30,** 9, 1093-1104.

Flynn, B.B., and Jacobs, F.R., 1987, An Experimental Comparison of Cellular (Group Technology) Layout with Functional Layout. *Decision Sciences*, **18,** 4, 562-581.

Jacobs, F.R., and Bragg, D.J., 1988, Repetitive Lots: Flow Time Reductions Through Sequencing and Dynamic Batch Sizing. D*ecision Sciences*, **19**, 2, 284-291.

Kannan, V.R., and Ghosh, S., 1996, A Virtual Cellular Manufacturing Approach to Batch Production. *Decision Sciences*, **27,** 3, 519-539.

Karmarkar, U., Kekre, S., Kekre, S., and Freeman, S., 1985, Lot Sizing and Lead Time Performance in a Manufacturing Cell. *Interfaces*, **15**, 2, 1-9.

Mihram, G.A., 1974, Blocking in Simular Experimental Designs. *Journal of Statistical Computer Simulation*, **3**, 29-32.

Morris, J.S., and Tersine, R.J., 1990, A Simulation Analysis of Factors Influencing the Attractiveness of Group Technology Cellular Layouts. *Management Science*, **36**, 12, 1567-1578.

Morris, J.S., and Tersine, R.J., 1989, A Comparison of Cell Loading Practices in Group Technology. *Journal of Manufacturing Operations Management*, **2**, *299-313.*

Pegden, C.D., 1987, *Introduction to SIMAN. (*Sewickley, PA: Systems Modeling Corporation).

Sassani, F., 1990, A Simulation Study on Performance Improvement of Group Technology Cells. *International Journal of Production Research*, **28**, 2, 293-300.

Shafer, S., and Charnes, J.M., 1993, Cellular Versus Functional Layouts Under a Variety of Shop Operating Conditions. *Decision Sciences*, **24**, 3, 665-682.

Suresh, N., 1992, Partitioning Work Centers for Group Technology: Analytical Extension and Shop Level Investigation. *Decision Sciences*, **23**, 2, 267-290.

Suresh, S., and Meredith, J.R., 1994, Coping with the Loss of Pooling Synergy in Cellular Manufacturing Systems. *Management Science*, **40**, 4, 466-483.