Faculty Working Paper 91-0121

Countering the Negative Impact of Intercell Flow in Cellular Manufacturing

Oscar Garza
Department of Business Administration
University of Houston

Timothy L. Smunt
Department of Business Administration
University of Illinois

Bureau of Economic and Business Research
College of Commerce and Business Administration
University of Illinois at Urbana-Champaign

BEBR

FACULTY WORKING PAPER NO. 91-0121

College of Commerce and Business Administration

University of Illinois at Urbana-Champaign

February 1991

Countering the Negative Impact of
Intercell Flow in Cellular Manufacturing

Oscar Garza*

and

Timothy L. Smunt**

Department of Business Administration

* College of Business Administration, University of Houston, 4800 Calhoun Street, Houston, TX 77204-6282

** College of Commerce and Business Administration, University of Illinois, 1206 South Sixth Street, Champaign, IL 61820

COUNTERING THE NEGATIVE IMPACT OF INTERCELL FLOW IN CELLULAR MANUFACTURING

EXECUTIVE SUMMARY

Although there are numerous studies that address the problems of optimal machine grouping and part family classification for cellular manufacturing, little research has been reported that studies the conditions where cellular manufacturing is appropriate. Flynn (1984) was one of the first to address this issue through a simulation modeling study, and although she did not specifically control for the effect of intercell flow, i.e. the proportion of operations that must be completed for a part outside its assigned cell, the model developed in these studies resulted in large amounts of intercell flow. Most recently, Morris and Tersine (1990) also addressed the desirability of cellular manufacturing under select manufacturing environments, but they did not address the impact of intercell flow. In the Morris and Tersine study, most environments tested resulted in system performance degradation when a traditional job shop with a process layout was converted to cellular manufacturing -- even though their modelling assumptions required all operations to be completed within one cell. In practice, intercell flow typically will be present after a large-scale conversion unless many additional machines are purchased to allow each cell to process the complete set of tasks for all parts in a family. Intercell flow is one major factor contributing to cellular manufacturing system performance degradation. In our study, we seek to fill the gaps between the prior simulation studies of cellular manufacturing system performance. We do this by 1) illustrating the negative impact of intercell flow when operating in a wide range of cellular manufacturing environments, and 2) indicating how changes in other operating factors caused by the conversion of a job shop to cellular manufacturing may counter the negative impact of intercell flow. Indeed, we show that many conditions exist where cellular manufacturing can achieve better system performance than a traditional job shop. However, our experiments also point out, like the previous studies, that a conversion to cellular manufacturing can easily degrade system performance -- unless other environmental factors are simultaneously changed to counter the negative impact of intercell flow and other problems caused by conversion to cellular manufacturing.

Simulation experiments were designed to accomplish these two objectives. We tested the effect of independent variables including intercell flow level,

setup time, processing time variability, job size, material handling time, the reduction of setup time made possible by conversion to cellular manufacturing, and product-mix stability. We found that a conversion to cellular manufacturing is a good alternative to job shop manufacturing when the conversion results in much lower processing time variability, in a great reduction in setup times, or when small batch sizes are desirable. Further, we found that, in many cases, the performance of cellular manufacturing as measured by Mean Flow Time or Work-In-Process inventory is better than that of a job shop when the conversion to cellular manufacturing results in a low level of intercell flow -- even when other operating factors do not improve after the conversion. This notion substantiates the objective of many cell formation techniques to minimize the level of intercell flow. Finally, we show that the effect of product-mix variation to be most detrimental to system performance when operating in a cellular mode of manufacturing.

Countering the Negative Impact of Intercell Flow in Cellular Manufacturing

1. INTRODUCTION

Cellular manufacturing (CM) is an application of Group Technology (GT) in which similar parts are grouped into part families and are separately processed in manufacturing subsystems called cells. Although a good deal of prior research has been devoted to the classification of parts into families or to the grouping of machines into cells (for example, see Burbidge (1971), McAuley (1972), (1973), King and Nakornchai (1982), Kusiak (1987), Seifoddini (1989), Vakharia (1986), and Wemmerlov and Hyer (1986)), there has been little research in the process design area that investigates the environments where cellular manufacturing performs better than does a traditional job shop using a process layout (Wemmerlov and Hyer, 1987). In this paper, we discuss a comprehensive simulation study that tests various environmental attributes that impact relative performance differences between production in a traditional job shop mode and production in a CM mode. Unlike previous studies (see Flynn (1984), Flynn and Jacobs (1986, 1987) and Morris and Tersine (1990)), we explicitly model and test various levels of intercell flow, i.e. the proportion of operations that must be completed for a part outside its assigned cell.

In cellular manufacturing, since setups can be simplified by dedicating the machines in a cell to a part family with similar manufacturing attributes, the reduction in setup time is often cited as a major contributing factor to a reduction in work-in-process inventory (WIP) and in mean flow time (MFT). However, when conversion to cellular manufacturing results in intercell flow, some parts must visit more than one cell, eliminating part of the setup time reduction benefits from dedication. At the extreme of an infinitely high intercell flow level, the same number and degree of setups are incurred as in a job shop.

Numerous disadvantages may arise from the use of cellular manufacturing, including the need for additional machines or a loss of flexibility in dealing with product-mix changes -- resulting from the increase in resource usage variance caused by dedication of specific machines to the manufacture of groups of parts. In order to counter the negative effects caused by dedication in cellular manufacturing, improvements in other environmental attributes must occur such as reduced material handling times, reduced variability of processing times, or reduced setup times. In addition, cellular manufacturing may become beneficial due to a marketing need for small order sizes or to increased operator responsibility and increased job satisfaction, resulting in increased product quality and worker productivity. We first illustrate the negative effects of using cellular manufacturing under various conditions, then we indicate the relative improvements required in various environmental attributes that must occur (and perhaps would in practice) when converting to cellular manufacturing.

2. RECENT STUDIES ON CELLULAR MANUFACTURING PERFORMANCE

In earlier prior research of cellular manufacturing process design issues, Flynn (1984) and Flynn and Jacobs (1986, 1987) investigated the situation where a job shop with a process layout was converted to CM. In their studies, they evaluated three job shop environments for possible conversion to cells. They found that CM performed better in terms of average move (material handling) time and average setup time than the original job shops. However, the job shops performed better in terms of queue related variables, including average waiting time. The effect of waiting time outweighed the effects of move time and setup time in their study, resulting in job shops with better MFT and WIP performance than their cellular counterparts. Note that in their model most parts were required to visit many different cells, resulting in large amounts of intercell flow. Although they explicitly optimized facility layout (using CRAFT) and measured move distances, the effect of material handling time on MFT was relatively small in their models. They did not test various levels of intercell flow, nor did they test different levels of move times.

In a very recent paper, Morris and Tersine (1990) used a simulation model to test the effect of setup time levels, variance of part interarrival times, and material handling speed for a select few environments. In their research, eight problem environments were tested for each of the process and cellular layouts. They assumed that all parts were processed within one cell, i.e. no intercell flow. Only one environment resulted in CM outperforming the process layout. Due to the limited information given on some of the model's parameter settings, it is difficult to determine the underlying cause of their results. For example, it is not possible to determine the contribution to MFT that is caused by material handling time. Other design issues may have biased CM performance in their study. Due to their assignment method of parts to cells and machines to cells, bottlenecks may have been designed into the cellular shop were none existed in their job shop. CM with an unbalanced load will likely result in poorer performance. Another reason for their experimental results to favor a process layout lies in their utilization levels. They state that their overall utilization levels were in the 60-70% range. If these levels existed for both the job shop and the cellular shop models, then the dominant job shop performance can be understood. When a job shop is not congested, average wait time, and, therefore, MFT will be relatively small even though setup times are much larger than those in the cellular shop.

Other limited previous research has implicitly considered intercell flow, but only as a result of alternate routings of jobs in the shop (Ang and Willey, 1984; Gupta and Tompkins, 1982). However, intercell flow is not only the result of alternate routings of jobs. When job shops are converted to cellular shops, it may be possible that some of the cells formed cannot completely process all the products assigned to them, perhaps due to an insufficient number of a heavily demanded machine type to allocate to all cells. In these situations, jobs must go outside their assigned cell to complete their processing. In our experiments, we explicitly control the level of intercell flow caused by the lack of processing capability within a cell.

Wemmerlov and Hyer's (1989) survey of cellular manufacturing users found that the median level of intercell flow was ten percent (with a mean of about 20 percent) and that only ten percent of the surveyed shops processed parts completely within cells. It is also interesting to note that despite the benefits attributed to cellular manufacturing in this survey, almost half of the surveyed firms reported that cells constituted less than five percent of their operation. As firms continue to convert more of their process layout to cellular manufacturing, we believe that intercell flow will become increasingly problematic in practice since relatively fewer machines will be available for assignment to a cell, unless additional capital investment is made.

3. OBJECTIVE

We designed simulation experiments to test several factors that might affect system performance from a conversion to CM, especially intercell flow. We do not model material handling as a separate resource in our simulation studies, but we do consider reduction in material move times resulting from the use of cells and two levels of material handling times that might arise in practice. (Although the simulation studies discussed above did model the distance between machines explicitly, the impact of material handling time on MFT was insignificant in their final results.) Our primary objective in this research is to determine the levels of factors that are required to make conversion to CM attractive, especially those factors associated with setup reductions and process disruptions. From our results, we indicate relative levels of improvement that must occur in various factors in order for CM to become an attractive process design when intercell flow impacts negatively on MFT or WIP. We model the environment where shifting bottlenecks[1] occur and where conversion to CM does not cause long-term bottlenecks where none existed in the job shop mode. That is, balanced loads are maintained on all machines in all cells and departments. (Else, the problem can easily resort to an M/M/1 queuing scenario.)

Our objective in this research is twofold: 1) to illustrate the negative impact of intercell flow under a wide range of cellular operating environments, and 2) to indicate how improvements in other operating factors resulting from the conversion to CM can counter the negative impact of intercell flow.

We address the following questions in this research:

a. To what extent does the level of intercell flow affect cellular shop performance, as measured by MFT and WIP?

b. At what level of processing variability will cellular manufacturing provide improved performance over a traditional job shop?

c. Do constraints in job size, perhaps posed by marketing or other functions of the firm, affect the possible improvement in MFT when converting to cellular manufacturing from a job shop mode?

d. To what extent does the proportion of setup time to processing time affect the change in performance when a job shop is converted to a cellular shop?

e. To what degree must setup time be reduced for a conversion to cellular manufacturing to be beneficial?

f. Does the relative performance of cellular manufacturing improve when material handling time (as a proportion of processing time) increases?

g. At what point of product-mix instability does the conversion to cellular manufacturing become unwise?

4. EXPERIMENTAL DESIGN

A full factorial experiment was designed to answer questions a-f. The experiment includes five factors (independent variables): level of intercell flow

---

[1] These short-term bottlenecks are described in detail and have been called "implicit shocks" by Monahan and Smunt (1990).

(4 levels), major setup time (3 levels), processing time variability[2] (4 levels), job size (4 levels), and setup ratio, i.e. the proportion of setup time remaining after conversion to CM (4 levels). The levels of each of these factors are included in Table 1. For each set of factors, two simulations were run, one for a job shop and one for a cellular shop -- each one involving exactly the same products and machines. Ten repetitions were run for each combination of factors to reduce sample size errors. Therefore, the number of simulation runs for the cellular shop was (4 X 3 X 4 X 4 X 4 X 10) 7680 and for the job shop was (3 X 4 X 4 X 10) 480, for a total of 8160 runs. Note that it was not necessary to test the intercell flow and setup ratio factors in a job shop setting.

**** *Insert Table 1 about here* ****

Computer simulation was chosen as the methodology for this study in order to address large and complex manufacturing systems. These systems may include multiple machines of several types with sequence dependent setups. Two factory simulation models written in SIMSCRIPT were used in this study: a job shop model and a cellular shop model. (See Appendix 1 for specific assumptions of these models.) In every simulation run, the shop's load was balanced (i.e. the expected number of setups and utilization per machine were the same across all machines in the shop). We first model the situation where the material handling time required to move a batch of parts between cells and between departments ranges from 8% to 20% of processing time. We further test situations where material handling time is greatly increased -- perhaps due to insufficient material handling capacity resulting in long queue times for material movement. In these tests, material handling time is equal to 40% to 100% of processing time.

The number of machines was set at 24. These machines belong to 8 different machine types. Therefore, in the job shop model, there are 8 departments, each containing 3 machines of the same type. In the cellular shop model, machines were assigned to cells in groups of four, for a total of six cells. This cell size is within the range (4 to 6 machines) used by about half of the cellular manufacturing users surveyed by Wemmerlov and Hyer (1989). Machines were assigned to cells in such a way that the desired level of intercell flow was obtained by changing the process routings of some of the products (see Appendix

---

[2] We measure processing time variability by the Coefficient of Variation (CV).

FACTORS	LEVELS
Level of intercell flow	0.0, 0.1, 0.2, 0.3
(Major) Setup time (hours)	0.2, 0.4, 0.6
Processing time variability (CV)	0.0, 0.33, 0.67, 1.0
Job size (units)	10, 15, 20, 25
Setup ratio (ratio of minor to major setup time)	0.1, 0.3, 0.6, 0.9

Table 1. Levels of the simulation factors

2). This procedure allows us to control the level of intercell flow for each individual experiment. Since it is our objective to study the effect of intercell flow, we explicitly determine the grouping of machines and routings of parts to obtain the desired level of intercell flow. In this way, we can ensure that the shop load remains completely balanced. We kept the number of operations per part and the number of machines per cell equal in a further effort to eliminate long-term bottleneck conditions and confounding effects. A total of 60 products was processed, with each product requiring 4 operations.

The interarrival rate of orders was adjusted to give a target shop process utilization of 60% for every combination of factor levels tested. Total utilization varied between 62% and 95% for the shops modeled in this work. This is consistent with typical values found in practice and with levels used in prior research studies (Flynn, 1987b). In order to achieve a 60% of process utilization, the demand rate per product was set at 1200 units per simulated year (2000 hours).

In testing for steady state conditions, we found that the initialization period of 36,000 completed jobs (about 10 years of operation assuming operation of 2000 hours per year for a job size of 20 units) was sufficient in all factor combinations. Performance variables were collected thereafter every 3,600 completed jobs (about 1 simulated year for a job size of 20 units) for a total of 10 repetitions. Each of the repetitions included sufficient completed jobs to ensure independence from other repetitions. The simulation runs required approximately 150 CPU hours on a VAX 8810.

4.1 Job Shop Model Specifications

The job shop model groups machines by type in departments (i.e. process layout). Each department may include one or more machines of the same type and has one queue for incoming jobs. Each job has a routing of departments to visit for processing in a prescribed order. Each product type has its own routing. In our model, we do not generate due dates of jobs, but rather immediately release a job to the shop when it arrives. Before visiting a given department, the job joins the department queue and waits for an available machine. When a machine becomes available it is setup for the product type of the next job in the queue (a First-Come, First-Serve priority rule) and the job is then processed. When two or more machines within a department are available, an incoming job searches for a machine already setup for that job (if any). The setup time is zero when the last product processed at a machine is the same as the next to be processed. When this is not the case, a major setup time is incurred.

When a job finishes processing in a department, it is transported with a given level of material handling time to the queue of the next department in its process routing. This sequence of operations is repeated until the job visits all the departments included in its process routing. Each product visits 4 departments before leaving the shop.

4.2 Cellular Shop Model Specifications

In the cellular shop model, machines of different types are assigned to cells and each cell is dedicated to a part family. As a result of dedication, we assume that each machine has tooling designed to reduce setup times, but only when members of the assigned part family are processed. This reduced setup time is called a minor setup time. However, when a dedicated machine processes a job which does not belong to its assigned part family, we assume a major setup time is incurred. Major setup times are required in a cellular shop only when products are not completely processed within one cell. As it is the case in the job shop model, the setup time is zero when the last part processed in a machine is the same as the next to be processed. (Since the machines in the job shop are not dedicated, there are no minor setup times in that model.)

In the cellular shop, there is one family of parts assigned to each one of the 6 cells. Each of these families includes 10 parts. Some parts are completely processed in the cell to which they are assigned. However, other parts may need processing outside their assigned cell. For these parts, half of the operations are completed in the cell to which they are assigned, and the other half in a different cell. The level of intercell flow is increased by changing the process routings of some products, in such a way that more and more products require processing in more than one cell. The process routings for each level of intercell flow are included in Appendix 2. Each cell is a unidirectional flow line (i.e. no backflow) and each product visits either one or two cells. While, in practice, the number of cells used by a particular part may vary, we designed our simulation model such that no loss of generalizability occurs with our assumption.

5. RESULTS

The main performance variables collected in both models were mean flow time and work-in-process inventory. We define flow time as the time between a job arrival and the time when the job finishes processing. MFT is the mean flow time for all jobs finished within the simulation period. WIP is the time-weighted average number of unfinished units of any product type in the system during the simulation period. Both MFT and WIP reduction were selected among the most common reasons for establishing manufacturing cells in a recent survey of cellular manufacturing users (Wemmerlov and Hyer, 1989). In our studies, we found that MFT was highly correlated with WIP, and we do not report WIP results here. However, these results are given in detail in Garza (1990).

In order to determine if a given set of shop factors performed better in the cellular shop than in the job shop, a "percentage improvement in MFT" variable was calculated. For simplicity, we refer to this variable as **PIMFT**. PIMFT is defined as:

$$\textbf{PIMFT} = \frac{100 * (\text{MFT in job shop} - \text{MFT in cellular shop})}{\text{MFT in job shop}}$$

A value of PIMFT larger than zero implies that the conversion from job shop to cellular shop resulted in an improvement in MFT.

Analysis of Variance (ANOVA) was used to test significance of PIMFT.[3] The Ryan-Einot-Gabriel-Welsch (REGW) multiple range test (Schlotzhauer and Littell, 1987) for each of the factors was also run. All main effects and first order interactions were found to be significant at the 0.05 level. Furthermore, the REGW tests show that for each factor there is a significant difference in PIMFT between any pair of levels considered.

---

[3] We tested the normality and homogeneity assumptions for ANOVA. We plotted the variances from each cell and determined that there were insignificant differences, thus meeting the homogeneity of variance assumption for an F-test. We ran χ^2 tests on the residuals to determine whether or not they came from a normal distribution. Although we obtained a high χ^2 value (significantly different), by observation of the plot of the residuals we found that they were distributed in a leptokurtic manner. Transformations helped reduce concentration of residuals near 0.0, but did not lower the χ^2 sufficiently. Based on the known robustness of the F-test and the fact that our p-values were quite low (.0001 in most cases), we feel that the level of significance we report is still accurate.

5.1 Intercell Flow

Four levels of intercell flow were considered in the cellular shop model: 0.0, 0.1, 0.2, and 0.3. A level of 0.1, for example, implies that for the average product, ten percent of its required operations are done outside its assigned cell, resulting in increased setup times, increased material handling, and increased overall congestion in the shop.

In Table 2a, the full factorial results are shown by each factor and with intercell flow. Note that only six cells (first-order interactions) in this table indicate positive PIMFT. Five cells appear in the 0.0 intercell flow column for low values of setup ratio, job size, CV, and for the highest value of major setup time. One occurrence appears in the 0.1 intercell flow column for the lowest CV level. We do not conclude from these results that conversion to CM does not have the potential of improving system performance. Rather, it is important to investigate higher order interactions to gain insight into the types of improvements that must occur in environmental attributes when converting to CM for such conversion to improve performance. Note that the number of cells that indicate positive PIMFT in Table 2b more than doubles, where average PIMFT data is shown only for a setup ratio=0.1. Clearly, results from any simulation study are driven by the model specifications and the factor levels tested. We believe that our model and choice of factor levels are reasonable, but we also note that it is critical to analyze the detailed data for further explanation of relative system performance.

When looking at the detailed experimental data (768 cellular shop operating conditions), 158 (21%) resulted with a positive PIMFT. Furthermore, of the 158 operating conditions with a positive PIMFT, 90 resulted with a PIMFT greater than 10% upon conversion to cellular manufacturing. The combinations of factor levels that resulted with CM outperforming the job shop typically occurred for zero or low intercell flow. 51.3% of the positive PIMFTs were for scenarios with no intercell flow, 27.8% of the positive PIMFTs were for the 0.1 intercell flow case, 13.3% of the positive PIMFTs were for the 0.2 intercell flow case, and 7.6% of the positive PIMFTs were for the 0.3 intercell flow case.

**** *Insert Table 2 about here* ****

The level of intercell flow resulting from a conversion to CM is typically a result of current conditions (number of machines, similarity of parts, etc.)

a. Full Factorial Results

FACTOR	LEVEL	INTERCELL FLOW 0.0	0.1	0.2	0.3	AVG.
	0.1	**+3.0**	-8.5	-18.2	-26.5	-12.6
SETUP	0.3	-3.6	-14.5	-23.6	-31.1	-18.2
RATIO	0.6	-15.2	-25.8	-33.8	-40.0	-28.7
	0.9	-31.7	-41.5	-47.5	-51.8	-43.1
	10	**+9.3**	-3.7	-14.2	-23.2	-8.0
JOB	15	-12.3	-23.7	-32.3	-39.2	-26.9
SIZE	20	-19.9	-29.7	-37.0	-42.8	-32.4
	25	-24.6	-33.2	-39.6	-44.3	-35.4
	0.00	**+17.1**	**+4.1**	-4.5	-10.6	1.5
CV	0.33	**+2.8**	-8.6	-17.5	-24.4	-11.9
	0.67	-19.9	-29.7	-38.1	-45.3	-33.3
	1.00	-47.6	-56.1	-63.1	-69.2	-59.0
MAJOR	0.2	-24.1	-31.8	-37.6	-41.7	-33.8
SETUP	0.4	-14.0	-25.2	-33.8	-40.3	-28.3
TIME	0.6	**+2.5**	-10.7	-21.0	-30.1	-14.8

b. SETUP RATIO=0.1 (only)

FACTOR	LEVEL	INTERCELL FLOW 0.0	0.1	0.2	0.3	AVG.
SETUP RATIO	0.1	**+3.0**	-8.5	-18.2	-26.5	-12.6
	10	**+28.8**	**+16.5**	**+5.0**	-5.4	11.2
JOB	15	**+4.0**	-8.5	-18.7	-27.7	-12.7
SIZE	20	-7.1	-18.0	-27.3	-34.7	-21.8
	25	-13.9	-24.0	-31.9	-38.0	-27.0
	0.00	**+26.5**	**+13.9**	**+4.6**	-2.6	10.6
CV	0.33	**+15.3**	**+3.8**	-6.2	-14.4	-0.4
	0.67	-3.3	-14.2	-24.3	-33.5	-18.8
	1.00	-26.8	-37.6	-46.9	-55.4	-41.7
MAJOR	0.2	-15.7	-24.6	-31.5	-37.1	-27.2
SETUP	0.4	**+1.8**	-10.7	-21.1	-29.8	-15.0
TIME	0.6	**+22.8**	**+9.7**	-2.1	-12.5	4.5

* PIMFT values first calculated on the individual simulation results for each combination of factor levels and then averaged for each factor level presented

Table 2. PIMFT average* results

and of the willingness of management to make investments in additional equipment or part redesign. Resulting intercell flow can also be minimized by using larger cell sizes, e.g. using two large cells vs. four smaller cells. However, tradeoffs exist with this option -- large setup time reductions cannot be expected when many different types of parts are processed on the same cell, nor can one expect that operation times will be similar.[3]

In Sections 5.2 - 5.5, we illustrate specific higher-order interactions and discuss the necessary changes that must occur to various environmental attributes for a conversion to CM to prove beneficial.

5.2 Processing Time Variability

Processing time variability of a job was specified at four levels of the coefficient of variation (CV): 0.0, 0.33, 0.67 and 1.00. We found that processing time variability can be a good surrogate for variability from other sources (see Monahan and Smunt (1990) and Garza(1990)). High coefficients of variation may be appropriate when using processing time variability as a surrogate for machine breakdowns, preventive maintenance, or rework. While it is true that machine breakdowns, for example, introduce forced idleness in the system rather than use capacity at varying levels (like that introduced by processing time variability), aggregate performance effects are similar. Since the intent of this study does not concern the identification of sources of performance degradation due to variance, but rather the overall effect of variance on CM performance, there is no need to separately model different sources of variance introduction. However, in practice, it may be necessary to model each source of variance individually so that specific changes for CM performance improvement can be appropriately identified in the actual process.

The first-order interaction results with intercell flow are shown in Table 2a. On average, PIMFT for a processing time variability (CV) of 0.0 (i.e. deterministic processing times) was 13.4, 34.8 and 60.5 percentage points higher than PIMFT for CVs of 0.33, 0.67 and 1.0, respectively. When processing time variability increases, short-term shifting bottlenecks form, resulting in an increase in MFT. Although both the job shop and the cellular shop MFTs increase with increasing processing time variance, the cellular shop is more sensitive to processing time variability than is the job shop. In the job shop, a part may

---

[3] We did not explicitly test or determine the cost of the options to reduce intercell flow in this study.

be processed on any of the multiple machines of the same type, providing a reduction in resource usage variance. When a temporary higher level of demand is placed on one cell, perhaps due to random market forces or random processing times, some machines in this cell will see long queues of WIP while similar machines in other cells remain idle. Since we do not allow alternate routings in the cellular shop model, the shifting bottleneck problem can cause the performance of CM to be worse than a job shop -- similar to the results that have been found in the research on stochastic assembly line in the past (see Smunt and Perkins (1985) for a review of this literature). If we allowed alternate routings to occur when a cell became congested, the cellular shop could not incur decreased MFT performance as long as the major setup times remained stable during this rerouting activity and material handling times did not increase over the job shop level.

Figure 1 further illustrates the extent of the effect of processing time variability across the four levels of intercell flow. (In this and following figures, we show effects where the setup ratio is 0.3, the major setup time is 0.4 hours, and the job size is 10 units since this is an environment that has moderate settings of factor levels and well-illustrates the conditions where conversion to CM results in both positive and negative improvements.) When the CV is 0.0 in both the job shop and CM, CM results in extremely high performance improvement, i.e. large PIMFT, for intercell flow levels of 0.0 and 0.1. It remains positive for intercell flow of 0.2, and is slightly negative for intercell flow of 0.3. As the Cvs increase simultaneously in both shop modes, the relative performance of CM degrades and is negative for all levels of intercell flow for the high CV level of 1.0.

However, Figure 2 indicates that if a conversion to CM results in lowering the CV, CM is attractive across all intercell levels for cell CVs of 0.0 and 0.33 assuming that the job shop CV remains at 1.0. Even if the cell CV can only be reduced from 1.0 to 0.67, the CM shop outperforms the job shop for intercell flow levels of 0.0 and 0.1 and has nearly the same performance as the job shop for an intercell flow level of 0.2. That is, when a good deal of variability exists in a job shop and a conversion to a cellular shop would decrease that variability, MFTs could be reduced even when the conversion results in some intercell flow.

***** Insert Figures 1 and 2 about here *****

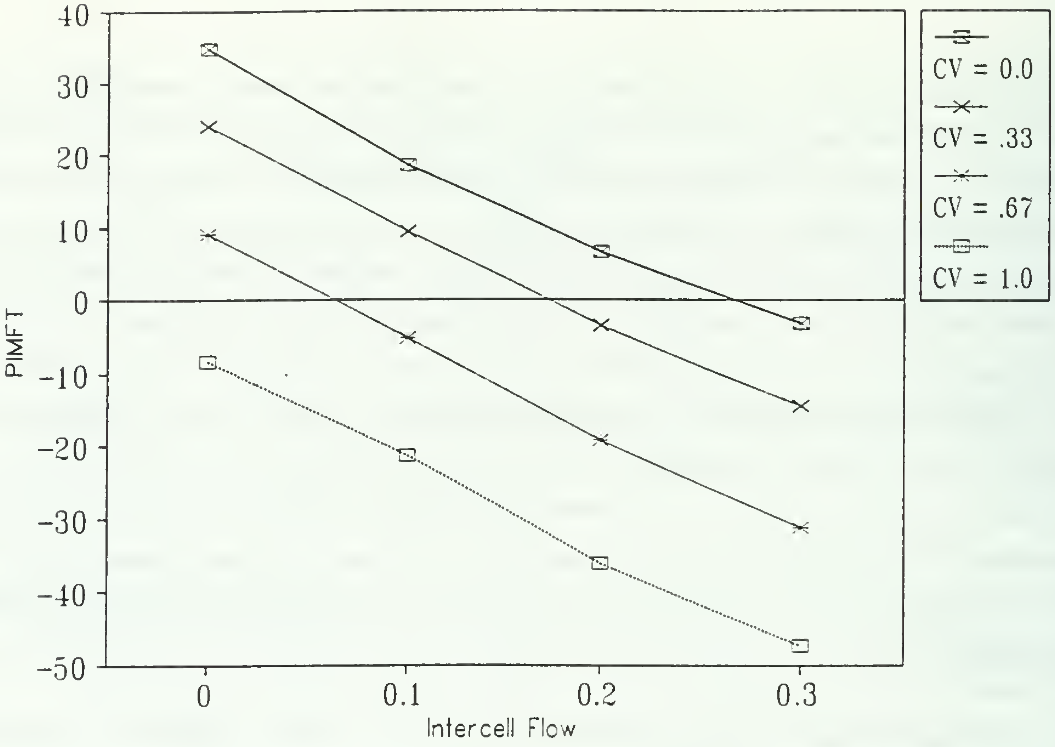

FIGURE 1
Effect of processing time variability when CV is the same in both job shop and cellular shop environments -- for case when setup ratio=0.3, major setup time=0.4 and job size=10

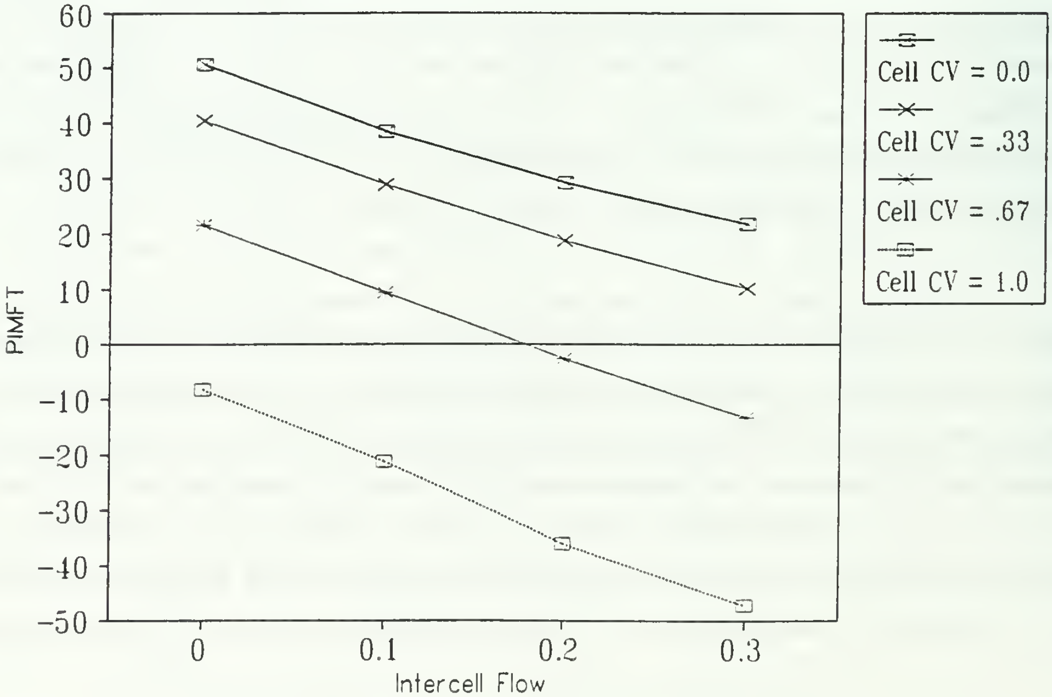

FIGURE 2
Effect of processing time variability when CV=1.0 in the job shop and varied for the cellular shop -- for case when setup ratio=0.3, major setup time=0.4 and job size=10

5.3 Job Size

We tested four levels of job size: 10, 15, 20 and 25 units. Larger job sizes lead to reduced total setup time in a shop (because less setups are needed), although it takes longer to process a larger job. In our experiments we assume that batch size equals the job size. We vary the job size, however, to investigate the impact of batch size reduction that becomes possible with the conversion to cellular manufacturing. The mean processing time for a unit of product is 0.1 hours per operation for all products. Therefore, the mean job processing time per operation is 1, 1.5, 2, or 2.5 hours for job sizes of 10, 15, 20, and 25, respectively.

PIMFT for shops operating with a job size of 10 units was, on the average, 18.9, 24.4 and 27.4 percentage points higher than PIMFT results for shops operating with job sizes of 15, 20 and 25 units, respectively (Table 2a). Job shops are inherently better than cellular shops at producing large job sizes. Cellular shops can better produce small job sizes due to lower setup times. We note the large difference (18.9 percentage points) between the PIMFT results for job sizes of 10 and 15 units in Figure 3. This difference is due mainly to a steep increase in MFT in the job shop caused by decreasing the job size of 15 to 10 units, since a very high shop utilization level is reached when producing in small lots.

**** *Insert Figure 3 about here* ****

Figure 4a illustrates the effect of converting to CM and of reducing job size simultaneously. When comparing to a job shop producing jobs of size 25 units, CM performance is substantially better when the job size in the cellular shop is reduced to 10 or 15 units for all levels of intercell flow. We believe that this particular comparison may be an unfair one since the job size must be the same in both the job shop or cellular shop, <u>if the choice of job size is marketing driven.</u> The comparisons made in Figure 3 are then more appropriate. However, if a firm is able to use any batch size that maximizes performance, then comparisons of the two modes should be made with batch sizes that separately optimize performance for each system. Generally, we found that in our model a job size of 20 or 15 for the job shop was best. Figure 4b shows that CM resulted in improved performance for most intercell flow levels when its job size was 10 or 15. We can conclude from these results, that the ability to reduce job size or the marketing need for job size reduction is a powerful argument for converting to CM.

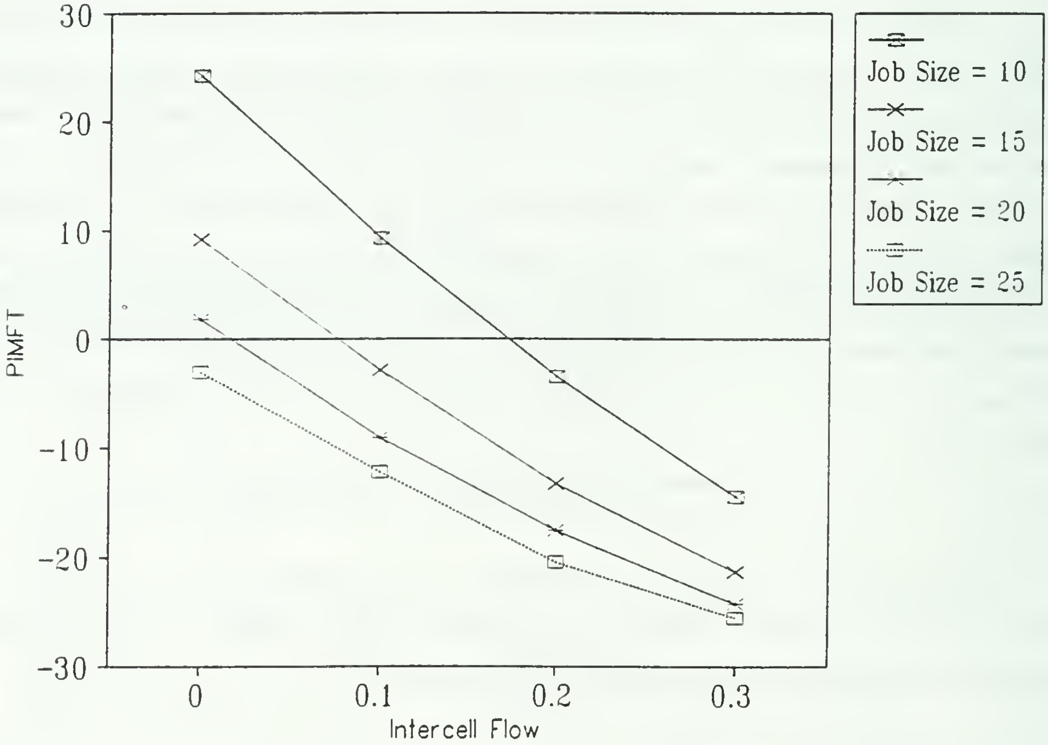

FIGURE 3

Effect of job size when it is the same in both job shop and cellular shop environments -- for case when setup ratio=0.3, major setup time=0.4 and CV=0.33

***** Insert Figure 4 about here *****

5.4 Setup Time

Three levels of major setup time are considered: 0.2, 0.4, and 0.6 hours. Note that the results of this work are not limited to the absolute values of job sizes and major setup times chosen, but rather to the ratio of major setup time to processing time. The combinations of job sizes and setup times used in this study (twelve in total) cover a range from 8% to 60% of this ratio. Values of this ratio within this range have been used in previous research involving shop simulation, including Flynn (1984), Lee (1985), and Jacobs and Bragg (1988). Since setup time is a component of MFT, a decrease in setup time results in reduced MFT and WIP, making the manufacturing system more responsive (since units get through the system faster) and reducing the need for a large finished goods inventory, if in a make-to-order environment.

PIMFT for a major setup time of 0.6 hours was, on the average, 13.5 and 19.0 percentage points higher than PIMFT for major setup times of 0.4 and 0.2 hours, respectively (Table 2a). Decreasing the setup time (as a proportion of processing time) simultaneously in both modes of production has a detrimental effect on PIMFT. Conversion to CM is most beneficial when the setup times require a large proportion of the machines' utilization in the job shop.

In Figure 5, we illustrate the effects of major setup time for the moderate parameter settings to indicate that conversion to CM can result in positive PIMFT even when the major setup time is fairly low. However, the level of intercell flow after conversion must also be low for this to occur. Since the job shop is running smoothly with low major setup times, conversion to CM provides little potential for improvement. The problems associated with dedicating equipment in CM tend to dominate in producing a negative effect on MFT in these conditions. When major setup times are moderate to high, CM outperforms the job shop even with low to moderate levels of intercell flow.

****** Insert Figure 5 about here *****

5.5 Setup Ratio

We defined setup ratio as the ratio of minor to major setup time. Therefore, it is a measure of the potential setup time savings that can be realized in a cellular shop after dedicating machines to the production of a

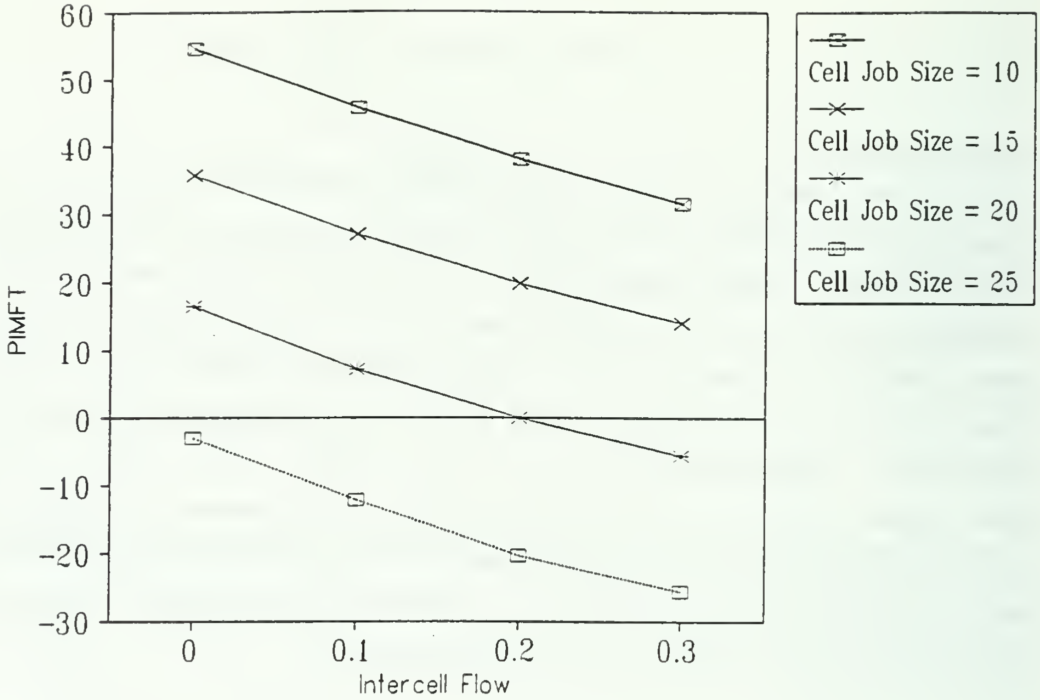

FIGURE 4a

Effect of job size when job size=25 for the job shop and job size varies in the cellular shop -- for case when setup ratio=0.3, major setup time=0.4 and CV=0.33

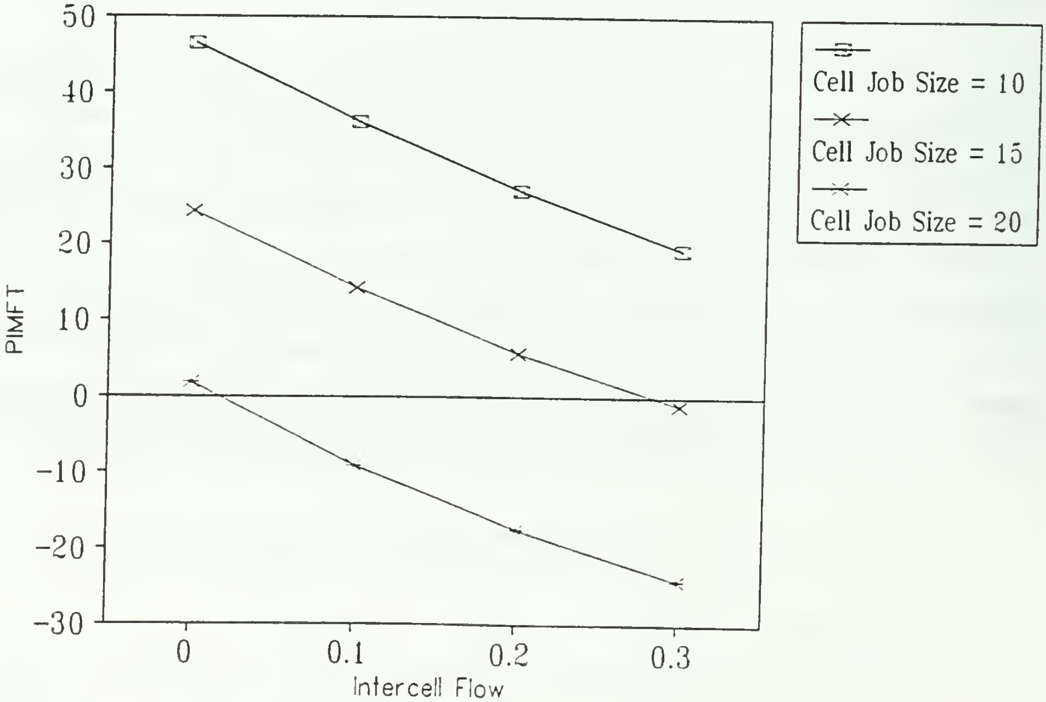

FIGURE 4b

Effect of job size when job size=20 for the job shop and job size varies in the cellular shop -- for case when setup ratio=0.3, major setup time=0.4 and CV=0.33

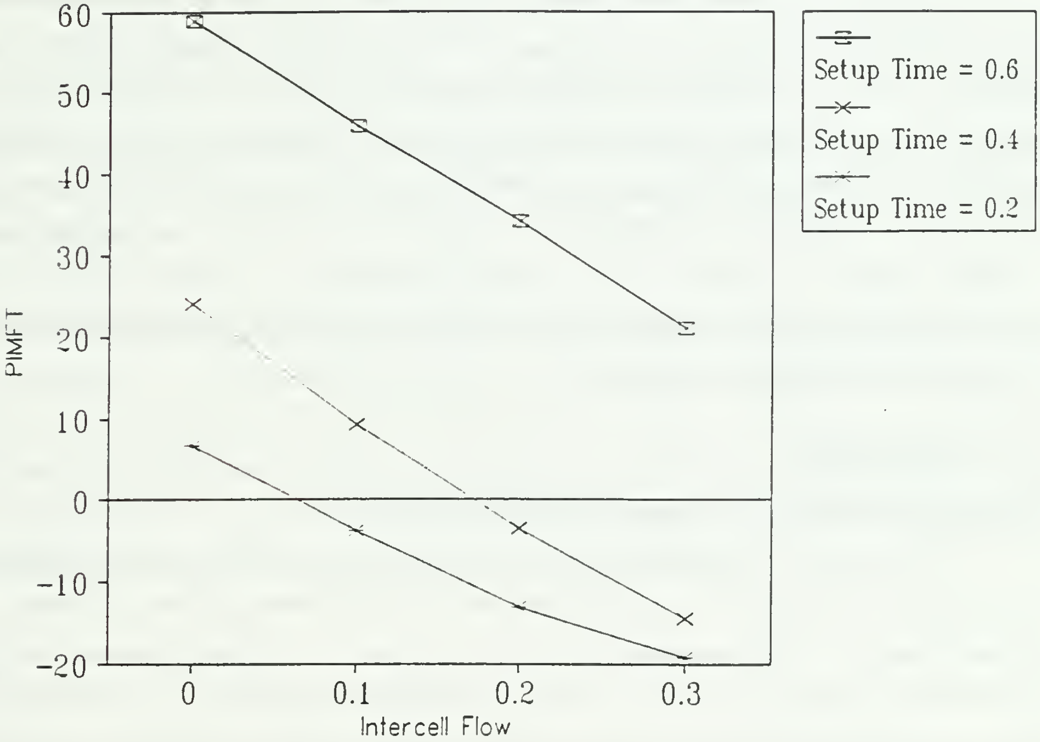

FIGURE 5

Effect of (major) setup time when it is the same in both job shop and cellular shop environments -- for case when setup ratio=0.3, CV=0.33 and job size=10 family of products. The smaller the setup ratio, the larger the reduction in setup times when a job shop is converted to a cellular shop. For example, setup ratio of 0.1 translates into a 90% reduction in setup time in the cellular shop each time a minor setup is needed. We tested four levels of setup ratio (ratio of minor to major setup time) in the main experiment: 0.1, 0.3, 0.6, and 0.9. A recent survey of CM users (Wemmerlov and Hyer, 1989) found setup ratios from 0.05 to 0.98, with an average of about 0.68. Therefore, the selected levels fall within actual practice.

Overall, PIMFT for a setup ratio of 0.1 was 5.6 percentage points higher than PIMFT for a ratio of 0.3, 16.1 percentage points higher than PIMFT for a ratio of 0.6, and 30.5 percentage point higher than PIMFT for a ratio of 0.9 (Table 2a). Capitalizing on setup time reductions is one of the main advantages of cellular manufacturing, and results of this research substantiate this notion. Therefore, production managers of traditional job shops operating with a process layout should be aware that a sizable reduction in setup times must occur before a conversion to cellular manufacturing typically should be considered an option to improve shop performance.

6. EXTENSIONS

6.1 The effect of material handling time

Previous studies in this area have not explicitly tested the effect of material handling as a proportion of processing/setup times. In our main experiment, the handling time required to move a batch of parts between departments (in the job shop) and between cells (in the cellular shop) was assumed constant and equal to 0.2 hours. The ratio of handling time to job processing time per operation is a function of job size and varied between 8% and 20%. Although this range was consistent with past research in this area and seems reasonable, we tested the effect of increasing material handling time to five times the original level for the moderate factor levels (setup ratio=0.3, major setup time=0.4, and processing time CV=0.33). We did this to illustrate the effect of additional flow time that might occur due to limited material handling capacity.

T-tests were completed and indicated that PIMFT at the base case (8% to 20% of processing time) is significantly different at the .05 level from the PIMFT at higher level of the ratio of handling time to processing time. Figure 6 includes PIMFT results for both material handling time levels. Note that for the original material handling time level of 0.2 (Figure 6a) only small job size scenarios show a positive PIMFT. However, as material handling time increases as a proportion of processing time (Figure 6b), a majority of the scenarios indicate that a conversion to CM improves MFT performance, even those with high intercell flow.

**** *Insert Figure 6 about here* ****

6.2 The effect of product-mix instability.

In our main experiments, we assumed that the expected demand for each product was constant and that the shops were always operating with balanced loads. However, shops operating with workload imbalances are common in practice. Permanent changes in product-mix or short-term demand changes due, for example, to a product promotion may result in workload imbalances. Shops operating with workload imbalances will develop long-term bottlenecks, resulting in system performance degradation.

We expect the negative impact of workload imbalances due to external forces to be more pronounced in the cellular shops than in the job shops. Due to dedication of machines to part families in a cellular shop, machines of the same type (but located in different cells) may work at very different utilization levels. This cannot occur in a traditional job shops since similar machines are grouped in departments and share the load of the department.

We designed an experiment to explicitly study the effect of product-mix changes on MFT in both a cellular setting and a job shop setting. The shop operating conditions considered include a job size of 15 units, a setup time of 0.6 hours, a CV of 0.33 and a setup ratio of 0.3. For this condition, conversion to cellular manufacturing was beneficial under stable product-mix (full factorial experiment). To test product-mix variation, we increased the average demand of three families (to a "high" demand level) while decreasing the average demand of the other three families (to a "low" demand level) by the same amount, keeping total demand unchanged. The change in the demand of each family constitutes a product-mix change which we measure by a demand ratio, defined as the ratio of high demand to low demand. The larger the demand ratio, the larger the product-mix change. In this experiment, we started with a scenario where the cellular shop performed better than the job shop, then gradually unbalanced the product-mix in order to study the MFT performance of both shops.

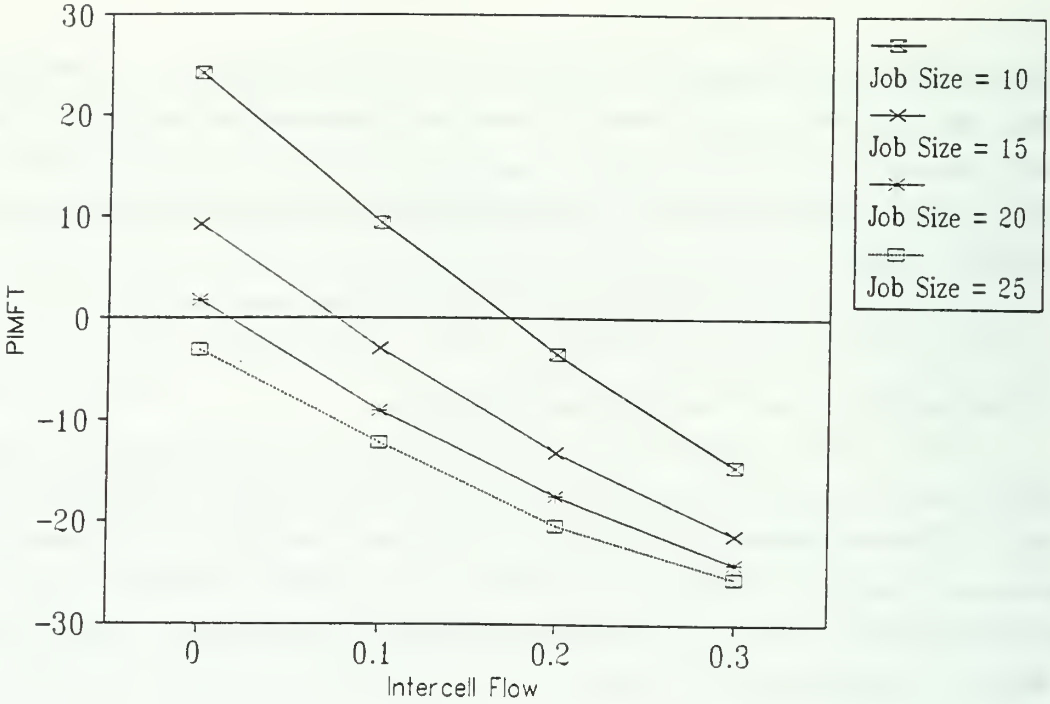

FIGURE 6a

Material handling time = 0.2 -- for case when setup ratio=0.3, major setup time=0.4 and CV=0.33

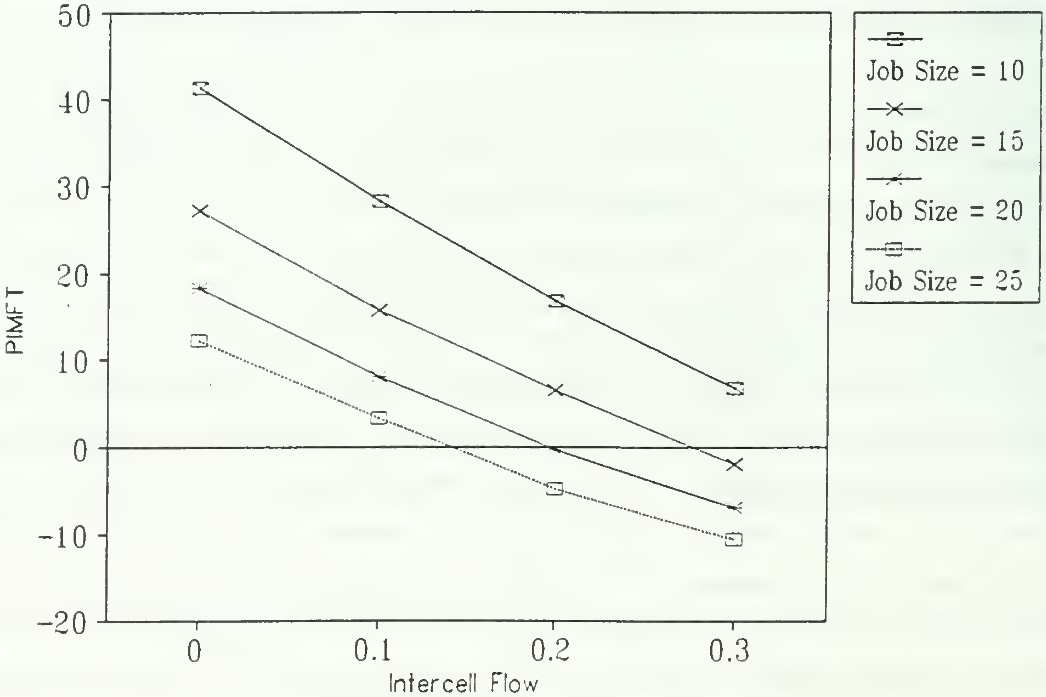

FIGURE 6b

Material handling time = 1.0 -- for case when setup ratio=0.3, major setup time=0.4 and CV=0.33

Figure 7a shows the MFT results as the product-mix becomes unbalanced. When the product-mix is balanced (i.e. demand ratio = 1), the cellular shop has better MFT performance than the job shop in this environment. As the demand ratio is increased, MFT performance degrades in both shops. However, the rate of MFT increase with demand ratio is much lower in the job shop. The difference in slopes results in a crossover of the MFT curves at a demand ratio of about 1.9. Figure 7b illustrates the maximum department process utilization % for a job shop and the maximum cell process utilization % for a cellular shop as the demand ratio increases. In the cellular shop, a cell working on a part family with high demand will experience sharply increased process utilization. However, in the job shop, a department visited by one or more parts with high demand also experiences increased process utilization, but at a smaller rate. Since the department has three machines, it is not only visited by parts with high demand, but also by parts with low demand which dampens the utilization effect of the product-mix change.

***** Insert Figure 7 about here *****

The above evidence substantiates that job shops are better prepared to sustain changes in product mix than are cellular shops, unless provisions are made to allow alternate routings without great increases in major setup times or additional equipment capacity is purchased. Otherwise, cellular shops may be preferred only under conditions of stable product mix or minor product mix changes.

7. CONCLUSIONS

We posed seven questions in Section 3 to help direct our research. We conclude with summary answers to them.

a. When a conversion to cellular manufacturing results in intercell flow, performance of the cellular system will likely be worse than that of a traditional job shop with a process layout. Our simulation results confirm that even small amounts of intercell flow can have a substantially negative impact on mean flow times (and WIP levels) for many conditions, especially those associated with high processing time variability and large job sizes (Table 2 and all Figures).

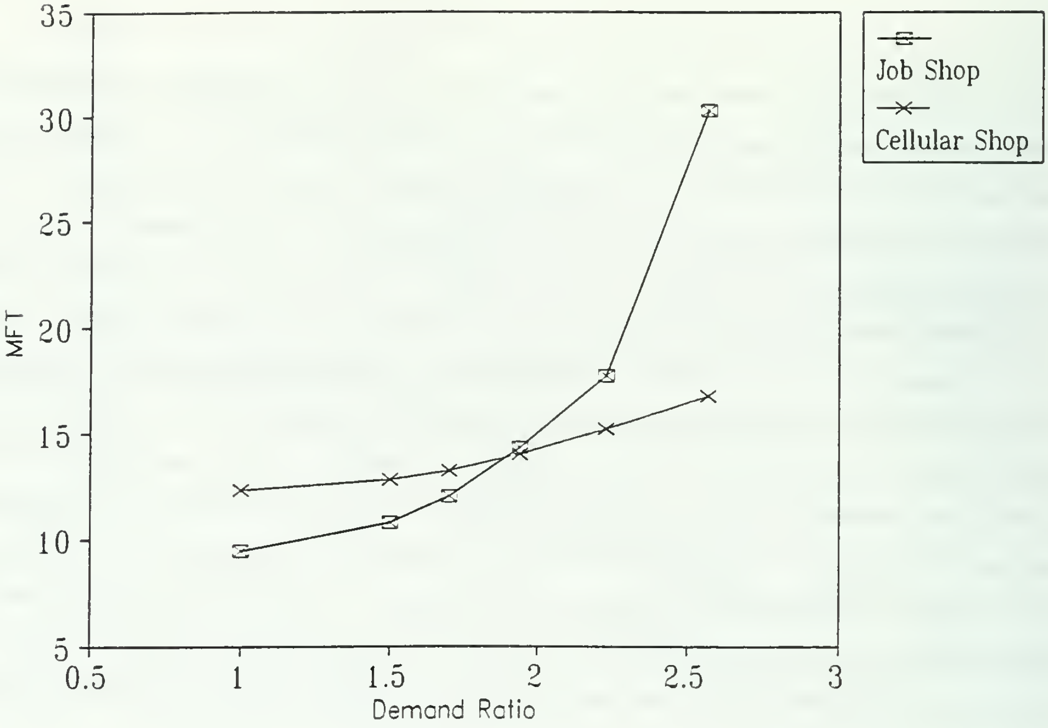

FIGURE 7a
Effect of product-mix instability on MFT as the demand ratio (high volume product to low volume product) increases

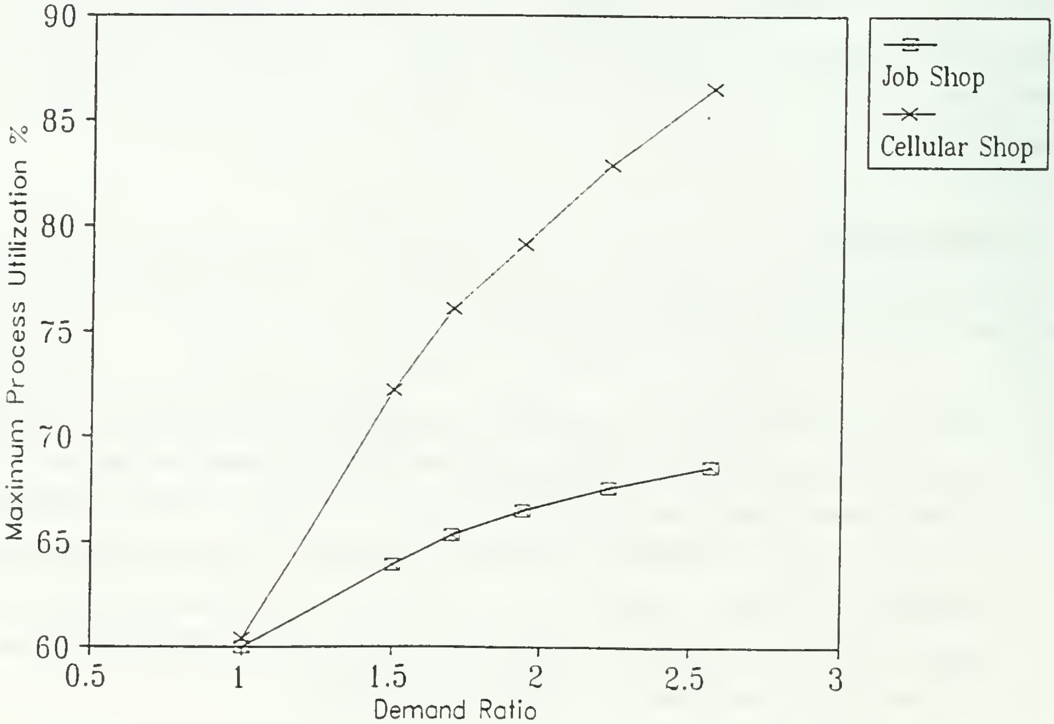

FIGURE 7b
Effect of product-mix instability on process utilization as the demand ratio (high volume product to low volume product) increases

b. However, our results also point out that by reducing processing time variability, by as little as 1/3 the amount in the job shop, cellular manufacturing can outperform a job shop mode for low intercell flow levels and moderate levels of other operating factors (Figure 2). Further, as processing time variability is reduced by 50% or more, cellular manufacturing outperforms the job shop for all intercell flow levels tested in the moderate operating condition.

c. We also found that cellular shops are best suited for small job size (batch size) production. This can be expected since the setup times will be lower in the cellular environment. This effect was somewhat small, however, when both the job shop and cellular shop were constrained to use the same job size (Figure 3). In this case, cellular manufacturing outperformed the job shop for small job sizes and low intercell flow levels. Looking at the situation where job sizes were large in the job shop and a conversion to cellular manufacturing was an impetus for smaller batch sizes, the performance of the cellular system further improved for all levels of intercell flow (Figure 4). We advise caution on this apparent effect. Although many firms have reported performance improvement when converting to cellular manufacturing, the <u>simultaneous</u> process redesign and lowering of batch size may be confounding the results. Perhaps the optimal lot size (with respect to MFT) for the job shop was not being used, reducing the potential performance of the job shop. Although we suggest further studies on this issue, i.e. more thorough comparisons of job shops and cellular shops in optimal batch size environments, it is quite difficult to determine, *a priori*, the best batch size to use in complex systems. Monahan and Smunt (1990) directly address this issue through simulation studies of numerous types of process designs.

d. Cellular shops performed better than did job shops when a high proportion of setup time to processing time existed in the job shop. Again, this result is expected since a main advantage of cellular manufacturing is the reduction of existing setup times. However, we also observed that for the moderate operating conditions, a 1/3 reduction of major setup times (from 0.6 to 0.4 hours in our experiment) could result in the job shop going from extremely poor relative performance to better performance than that of a cellular shop for medium to high intercell flow levels (Figure 5).

e. Of course, the proportion of setup time that can be reduced by cellular manufacturing is also an important factor in resulting performance. In Table 2a, we saw that few cells indicated attractive cellular manufacturing performance. However, when only the low setup ratio (large setup time reductions) was used to calculate average performance, many more cells showed that a conversion to cellular manufacturing was beneficial.

f. We performed some limited tests on increased material handling time. When material handling time is quite high in a job shop, the conversion to cellular manufacturing becomes attractive at most intercell flow levels, especially when producing small job sizes (Figure 6b). If material handling times are a small proportion of MFT, as it was in previous studies and in our full factorial experiment, only those conditions with small job size and no or little intercell flow favored cellular manufacturing (Figure 6a).

g. Finally, we found that cellular manufacturing can handle a relatively large imbalance in product-mix demand ratio (up to 2-to-1 for a moderate set of conditions as seen in Figure 7a). However, we also found that a job shop's performance is relatively stable across a wide range of product-mix stability. The ability to process any type of part in a department provides a flexibility that is lost when converting to cellular manufacturing.

In summary, the results of our study indicate that although the existence of intercell flow has a negative effect on cellular manufacturing performance, improvements in other operating factors can counter this negative impact. As Greene and Sadowski (1984) pointed out a few years back, "... design or redesign of a job shop to a Cellular Manufacturing system remains rather difficult and theoretical." Our research does not provide a cookbook approach for converting to cellular manufacturing -- each situation in practice will be unique and require its own specific (simulation) analysis. However, our results do provide rough guidelines on the levels of improvement in certain operating attributes that are necessary when making this conversion.

8. FUTURE WORK

This research is the first step in identifying the effect of intercell flow on the performance of cellular manufacturing systems. Our reported results test the environment of stable demand conditions and one condition where product-mix changes. In ongoing research, we are comprehensively testing the effects of dynamic product demand and its effect on long-term imbalance in cellular manufacturing. Additional research on other factors concerning cellular manufacturing performance is still needed.

In this research we considered move times only, but did not consider the possible queue times that could occur in shops with substantial material handling equipment constraints. Under this condition, material handling queue time must also be determined in order to better compare job shop performance to cellular shop performance. This type of analysis requires a comprehensive dual resource experiment. We are currently engaged in the design of simulation models that will explicitly test this issue. In this environment, we may find conditions where job shop material handling times are substantially larger than the ones we tested, giving further advantage to cellular manufacturing.

In our experiments, the handling time required to move a batch of parts between departments (in the job shop) and between cells (in the cellular shop) was assumed to be the same. In a job shop with an efficient process layout, departments are located so that the distance traveled by batches of parts between them is minimized. When a job shop is converted to a cellular shop, machines are rearranged into cells. The layout of the cells in the cellular shop could also be optimized to minimize the distance traveled by batches of parts between cells, but it is still possible that the handling time required to move a batch of parts between departments in the job shop is smaller than the one required to move a batch of parts between cells in the cellular shop. We have run preliminary experiments related to this issue (see Garza (1990)) and found that move times between cells must be considerably larger than move times between departments before a significant difference in PIMFT results is observed, since the number of intercell moves in a cellular shop is typically far less than the number of inter-department moves in a job shop.

The first-come, first-served rule was used in the main experiment of this research in both the job shop and cellular shop settings since it provides an upper bound on MFT performance. We expect that the best scheduling rules for use in a job shop may be different than those for a cellular shop. Some preliminary experiments using the "repetitive lots" scheduling rule (Jacobs and Bragg, 1988), instead of the first-come, first-served rule, showed that the use of the former resulted in an improvement in MFT in both the job shops and the cellular shops considered. However, in most of the conditions studied, the improvement in MFT in a cellular shop was larger than the improvement in a job shop operating with the same shop parameters. We do not expect this trend to be a norm for every operating condition. Differences in part variety in the queues, queue length and shop utilization, to name a few, affect the efficacy of the repetitive lots rule. We also have run some preliminary experiments (Garza (1990)) that indicates the effectiveness of the repetitive lots rule depends greatly on the operating conditions.

There is also a need to test the effect of adding machines to cells as a way of increasing the performance of a cellular shop. In this research we only considered the allocation of existing machines when forming cells. However, it is possible to add extra (new) machines to a cell to make it self sufficient and prevent parts from flowing between cells. The trade-off between the investment required for the new machines and the potential performance improvement is another important issue in the area of cellular manufacturing and one that requires further research. Further, if cell formation results in placing more than one machine of each type in a cell, the negative effect of processing time variability decreases since the cell design retains some features of parallel processing found in the job shop.

Clearly, numerous avenues of cellular manufacturing design research remain untravelled.

REFERENCES

Ang, C.L., and Willey, P.C.T., 1984, "A comparative study of the performance of pure and hybrid group technology manufacturing systems using computer simulation techniques", International Journal of Production Research, 22(2), 193-233

Burbidge, J.L., 1971, "Production flow analysis", The Production Engineer, April/May, 139-152

Carrie, A.S., 1973, "Numerical taxonomy applied to group technology and plant layout", International Journal of Production Research, 11(4), 399-416

Dudley, N. A., 1963, "Work-time distributions", International Journal of Production Research, 2(2), 137-144

Flynn, B.B., 1984, "Group technology versus process layout: a comparison using computerized job shop simulation", Unpublished Doctoral Dissertation, Indiana University, Bloomington, IN, USA

Flynn, B.B., and Jacobs, F.R., 1987, "An experimental comparison of cellular (group technology) layout with process layout", Decision Sciences, 18, 562-581

Flynn, B.B., and Jacobs, F.R., 1986, "A simulation comparison of group technology with traditional job shop manufacturing", International Journal of Production Research, 24(5), 1171-1192

Garza, O., 1990, "The effect of intercell flow on the performance of cellular manufacturing systems," Unpublished Doctoral Dissertation, Washington University, St. Louis, MO, USA

Greene, T.J., and Sadowski, R.P., 1984, "A review of cellular manufacturing assumptions, advantages and design techniques", Journal of Operations Management, 4(2), 85-97

Gupta, R.M., and Tompkins, J.A., 1982, "An examination of the dynamic behaviour of part-families in group technology", International Journal of Production Research, 20(1), 73-86

Jacobs, F.R., and Bragg, D.J., 1988, "Repetitive Lots: flow-time reductions through sequencing and dynamic batch sizing", Decision Sciences, 19, 281-294

King, J.R., and Nakornchai, V., 1982, "Machine-component group formation in group technology: review and extension", International Journal of Production Research, 20(2), 117-133

Kusiak, A., 1987, "The generalized group technology concept", International Journal of Production Research, 25(4), 561-569

Lee, L.C., 1985, "A study of system characteristics in a manufacturing cell", International Journal of Production Research, 23(6), 1101-1114

McAuley, J., 1972, "Machine grouping for efficient production", The Production Engineer, 51(2), 53-57

Monahan, G.E., and Smunt, T.L., 1990, "Product-process relations in batch manufacturing", University of Illinois, Working paper.

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

Schlotzhauer, S.D., and Littell, R.C., 1987, SAS System for Elementary Statistical Analysis, (SAS Institute Inc.)

Seifoddini, H., 1989, "A note on the similarity coefficient method and the problem of improper machine assignment in group technology applications", International Journal of Production Research, 27(7), 1161-1165

Smunt, T.L., and Perkins, W.C., 1985, "Stochastic Unpaced Line Design: Review and Further Experimental Results," Journal of Operations Management, 5(3), 351-373.

Vakharia, A.J., 1986, "Methods of cell formation in group technology: A framework for evaluation", Journal of Operations Management, 6(3), 257-271

Wemmerlov, U., and Hyer, N.L., 1989, "Cellular manufacturing in the U.S. industry: a survey of users", International Journal of Production Research, 27(9), 1511-1530

Wemmerlov, U., and Hyer, N.L., 1987, "Research issues in cellular manufacturing", International Journal of Production Research, 25(3), 413-431

Wemmerlov, U., and Hyer, N.L., 1986, "Procedures for the part family / machine group identification problem in cellular manufacturing", Journal of Operations Management, 6(2), 125-147

Appendix 1 - Assumptions of the Models

The main assumptions of both models (unless otherwise noted) are:

(1) Job orders of constant size arrive deterministically in the shop. The product type that each job order represents is sampled from the uniform distribution across the whole product-mix (60 products). Therefore, even though the expected total demand for each product during a simulation period is constant, job order arrivals for each product are random.

(2) A first-come first-served (FCFS) scheduling rule is used to select jobs from machine (cellular shop) and department (job shop) queues.

(3) The processing batch size equals the job size of incoming orders (job order size). Instead of batching orders, it is assumed that the company releases job orders as received. We do this to be able to explicitly determine the effect of batch size on system performance.

(4) Both major and minor setup times are deterministic. However, the processing time per job is stochastic with a Gamma distribution. This distribution is positively skewed for coefficients of variation smaller than one, which correlates with empirical evidence on unpaced task times presented by Dudley (1963). Furthermore, sampling from the Gamma distribution results in non-negative processing times.

(5) Handling time is deterministic. Incremental handling time is incurred when jobs are transported from one department to another in the job shop or from one cell to another in the cellular shop. Therefore, in the cellular shop, total handling time is a function of the level of intercell flow. It is further assumed that the time penalty for transporting jobs between departments in the job shops and between cells in the cellular shop is identical. Note that there are no handling requirements for jobs moving within a cell.

(6) There are no alternate routings in the cellular shop. Each product type has one and only one process routing. In the job shop, any machine of the same type can process a job which requires that machine type.

Appendix 2 - Process Routings

CELLULAR SHOP LAYOUT

cell 1	M1	M2	M3	M4
cell 2	M5	M6	M7	M8
cell 3	M9	M10	M11	M12
cell 4	M13	M14	M15	M16
cell 5	M17	M18	M19	M20
cell 6	M21	M22	M23	M24

JOB SHOP LAYOUT

dept A	dept B	dept C
M1	M8	M3
M17	M15	M11
M22	M24	M18
dept D	dept E	dept F
M7	M4	M2
M16	M6	M12
M21	M9	M14
dept G	dept H	
M5	M10	
M13	M20	
M19	M23	

NOTE: These layouts are not intended to represent the exact physical layouts of the shops but only the machines included in each cell (cellular shop) and in each department (job shop). In the job shop, machines within the same department are similar. For example, in dept. G, machines M5, M13, and M19 are similar. However, when the job shop is converted to a cellular shop, similar machines are included in different cells and "dedicated" to different families.

Product routings are included for each product (or group of products with the same routing). Machine numbers refer to the above layouts. Product routings included are for the cellular shop. Routings for the job shop are the same except that a part which needs to be processed in a machine included in one department, may be processed in any other machine within the same department (i.e. in any other machine of the same type).

Pij = product number j assigned to cell number i ---- (cellular shop)

Pij = product number (10i + j) ---- (job shop)

(i.e. P35 is product 5 assigned to cell 3 in the cellular shop and is product number 35 in the job shop).

PRODUCT(S)	ROUTING			
P10 - P19	M1	M2	M3	M4
P20 - P29	M5	M6	M7	M8
P30 - P39	M9	M10	M11	M12
P40 - P49	M13	M14	M15	M16
P50 - P59	M17	M18	M19	M20
P60 - P69	M21	M22	M23	M24

PRODUCT ROUTINGS FOR LEVEL OF INTERCELL FLOW = 0.0

PRODUCT(S)	ROUTING			
P10	M1	M2	M7	M8
P11	M9	M10	M3	M4
P12 - P19	M1	M2	M3	M4
P20	M5	M6	M11	M12
P21	M1	M2	M7	M8
P22 - P29	M5	M6	M7	M8
P30	M9	M10	M3	M4
P31	M5	M6	M11	M12
P32 - P39	M9	M10	M11	M12
P40	M17	M18	M15	M16
P41	M13	M14	M23	M24
P42 - P49	M13	M14	M15	M16
P50	M21	M22	M19	M20
P51	M17	M18	M15	M16
P52 - P59	M17	M18	M19	M20
P60	M13	M14	M23	M24
P61	M21	M22	M19	M20
P62 - P69	M21	M22	M23	M24

PRODUCT ROUTINGS FOR LEVEL OF INTERCELL FLOW = 0.1

PRODUCT(S)	ROUTING			
P10	M1	M2	M7	M8
P11	M9	M10	M3	M4
P12	M1	M2	M11	M12
P13	M5	M6	M3	M4
P14 - P19	M1	M2	M3	M4
P20	M5	M6	M11	M12
P21	M1	M2	M7	M8
P22	M5	M6	M3	M4
P23	M9	M10	M7	M8
P24 - P29	M5	M6	M7	M8
P30	M9	M10	M3	M4
P31	M5	M6	M11	M12
P32	M9	M10	M7	M8
P33	M1	M2	M11	M12
P34 - P39	M9	M10	M11	M12
P40	M17	M18	M15	M16
P41	M13	M14	M23	M24
P42	M21	M22	M15	M16
P43	M13	M14	M19	M20
P44 - P49	M13	M14	M15	M16
P50	M21	M22	M19	M20
P51	M17	M18	M15	M16
P52	M13	M14	M19	M20
P53	M17	M18	M23	M24
P54 - P59	M17	M18	M19	M20
P60	M13	M14	M23	M24
P61	M21	M22	M19	M20
P62	M17	M18	M23	M24
P63	M21	M22	M15	M16
P64 - P69	M21	M22	M23	M24

PRODUCT ROUTINGS FOR LEVEL OF INTERCELL FLOW = 0.2

PRODUCT(S)	ROUTING			
P10	M1	M2	M7	M8
P11	M9	M10	M3	M4
P12	M1	M2	M11	M12
P13	M5	M6	M3	M4
P14	M1	M2	M15	M16
P15	M13	M14	M3	M4
P16 - P19	M1	M2	M3	M4
P20	M5	M6	M11	M12
P21	M1	M2	M7	M8
P22	M5	M6	M3	M4
P23	M9	M10	M7	M8
P24	M5	M6	M19	M20
P25	M17	M18	M7	M8
P26 - P29	M5	M6	M7	M8
P30	M9	M10	M3	M4
P31	M5	M6	M11	M12
P32	M9	M10	M7	M8
P33	M1	M2	M11	M12
P34	M9	M10	M23	M24
P35	M21	M22	M11	M12
P36 - P39	M9	M10	M11	M12
P40	M17	M18	M15	M16
P41	M13	M14	M23	M24
P42	M21	M22	M15	M16
P43	M13	M14	M19	M20
P44	M13	M14	M3	M4
P45	M1	M2	M15	M16
P46 - P49	M13	M14	M15	M16
P50	M21	M22	M19	M20
P51	M17	M18	M15	M16
P52	M13	M14	M19	M20
P53	M17	M18	M23	M24
P54	M17	M18	M7	M8
P55	M5	M6	M19	M20
P56 - P59	M17	M18	M19	M20
P60	M13	M14	M23	M24
P61	M21	M22	M19	M20
P62	M17	M18	M23	M24
P63	M21	M22	M15	M16
P64	M21	M22	M11	M12
P65	M9	M10	M23	M24
P66 - P69	M21	M22	M23	M24

PRODUCT ROUTINGS FOR LEVEL OF INTERCELL FLOW = 0.3