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Analysis of Multi-Cell Production Systems Considering Cell Size and Worker Flexibility

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This simulation study investigates the performance of a number of multi-cell configurations generated by altering the cell size, worker flexibility and shop type, under a variety of experimental conditions. The experimental factors considered are product mix balance, due date tightness, and setup-to-processing-time ratio. The study is motivated by the challenges faced by an electronic manufacturer to design an efficient and effective multi-cell production system. The results demonstrate that everything else being equal, small cells perform better under low setup times and loose-to-moderate due date tightness levels, while larger cells perform better under high setup times and tight due date environments. Furthermore, the performance of larger cells is more robust with respect to due date tightness factor than that of smaller cells. It is also shown that the presence of some routing flexibility in the shop significantly enhances the performance of the small cells. However, shops with no routing flexibility need to be large to perform effectively, especially when facing constraints such as tight due dates and extreme product mix unbalance.

Significance: This paper investigates the performance of alternative multi-cell production systems in environments where several product families with variable demand are produced. The results demonstrate that significant improvements in efficiency and customer service can be achieved if the worker flexibility and cell size characteristics are matched to the production environment characteristics.

Keywords: Cellular Manufacturing, Multi-Cell Production System Performance, Cell Size, Worker Flexibility.

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1. INTRODUCTION

Partitioning production systems into manufacturing cells has been shown to result in several potential benefits (e.g., Greene and Sadowski 1984, Suresh and Meredith 1985, Shafer and Charnes 1993, Shafer and Charnes 1995, Wemmerlov and Johnson 1997). On the other hand, it has also been shown that the loss of pooling synergy in this process can be significant, resulting in performance deterioration that has to be carefully managed (e.g., Suresh 1991, Suresh 1992, Suresh and Meredith 1994). In summary, the advantages of cellular manufacturing have been demonstrated to be highly conditional on the shop parameters. Several studies have investigated the parameter ranges where cellular layouts can be inferior or superior to functional layouts (e.g., Flynn 1987, Morris and Tersine 1989, Morris and Tersine 1990, Suresh 1991, Suresh 1992, Suresh and Meredith 1994, Shafer and Charnes 1993, Morris and Tersine 1994, Shafer and Charnes 1995, Johnson and Wemmerlov 1996, Farrington and Nazemetz 1998, Kannan and Palocsay 1999). These studies have investigated the effects of a variety of factors such as lot sizes, setup times, variability in job arrivals and processing times, cross-training workers, labor assignment and dispatching rules, demand variation, and system configuration on the relative performance of cellular and functional layouts. For a complete review of the evaluation of functional versus cellular system performance literature, see Suresh (1998).

Unfortunately, the impact of cell size on the performance of multi-cell production systems has not been sufficiently studied. Only Suresh (1992) has considered cell size as an experimental factor in a study that compared the performance of an efficient functional layout with two cellular manufacturing systems. The results indicated that the cellular systems could be superior to the best of the functional layouts in certain parameter ranges. Specifically, larger cells, with some amount of routing flexibility within, performed better than excessively partitioned systems.

This research is motivated by the challenges faced by an electronics manufacturer to design an efficient and effective multi-cell production system. The manufacturer was in the process of building a new facility and was in the planning stages for the workcenter design including location of workbenches, equipment and electricity. When designing a multi-cell production system, the question of cell size arises, as decisions on the allocation of equipment, space and labor must be made. Furthermore, the cell size determination is tied to the number of families allocated to the cell and the approach used to assign families to cells. If only one major family is to be assigned to each cell, the number of cells must be equal or greater than the number of families. For example, managers could select cells of 12 workers and assign one primary product family to each cell. Alternatively, managers could form smaller cells of six workers, and assign one primary family to two cells. There are some obvious constraints associated with the cell size decision. For example, manual cells typically have less than 20 workers, and it is argued that the maximum effective number of workers is 15, given a larger number limits the ability of the cell to become a cohesive and effective work group (Hyer and Wemmerlov 2002).

A recent related study investigated the impact of worker and shop flexibility on different cellular manufacturing systems over a range of experimental conditions (Ruiz-Torres and Mahmoodi 2007). Three types of cell shops were considered: strict cell shops (where each cell is dedicated to producing only one product family), flexible cell shops (where each cell can produce multiple product families), and hybrid cell shops (where some of the cells are strict and the rest are flexible). Results indicated that there is no cell shop that outperforms others, under all experimental environments. However, flexible cell shops showed significant advantages when the setup times were low, while hybrid cell shops provided an excellent alternative when setup times and the product mix unbalance were at “moderate to high” levels. Finally, the strict cell shops demonstrated excellent performance when setup times were high, and the product mix unbalance was minor. Although this study provided many insights, its experimental design was limited and did not include such factors as cell size and due date tightness.

This research investigates the performance of alternative multi-cell configurations in an environment where several product families with variable demand are produced. Altering the cell size, the flexibility of workers assigned to the cells, and the shop type generated the different configurations. Note that while the motivation for this research is based on the challenges faced by an electronic manufacturer, the experimental factors are not restricted to the observed case. Instead, a more general set of parameters was considered based on the literature and our observations during several site visits of manufacturers located in the United States, Mexico and Japan.

The site visits focused on the development of their cellular approach, the allocation of workers to cells, and the procedures used to control daily and weekly production. The site visits, each taking at least a full day, typically included a presentation of production planning and logistics methods utilized by plant and line managers, observations of the production floor, and compilation of anecdotal data regarding the management system currently (and previously) used to control cells. The manufacturers visited were primarily involved in the automobile components and electronic sectors and are listed in the Acknowledgement Section. Considering that the observed sites were typically labor-intensive cellular manufacturing environments, the central element of the cell size decision was the number of workers allocated to the cell. Also, the equipment used in different cells were fairly similar, thus reconfiguring the equipment within a cell would enable that cell to produce parts from all the product families.

This research is significant as it provides insights regarding the relationship among various shop variables in multi-cell systems. As managers design production systems it is critical for them to understand how variables outside of their control such as product mix variability and due date tightness can impact their shop performance. We hypothesize that the environmental factors have significant impacts on the performance of the multi-cell production systems. Although the previous studies have provided many insights, the impact of the cell size on the performance of multi-cell production systems has not been sufficiently studied.

The cell size decision is very critical as it is typically linked to equipment location, inventory location, workstation design, acquisition of tools and equipment, and overall process flow design. Cell size decisions also affect production planning, engineering support, and even human resource decisions (e.g., incentive systems). In addition, the cell size decision is associated with the formation of product families.

The cell size decision must be coupled with other design and operational processes such as worker flexibility given their interaction may impact the shop performance. Worker flexibility allows managers to temporarily change the effective capacity of work areas by reallocating workers. This flexibility allows managers to match capacity requirements to fit the demand. The next element that must be considered in conjunction with the cell size and worker flexibility is the type of cells utilized in a multi-cell production system. While in many cases cells are primarily dedicated to a single family, in some environments cells are designed to produce multiple product families, providing another level of flexibility. In summary, the cell size, workers flexibility, and the cell type are major drivers in the performance of multi-cell production systems.

The remainder of the paper is organized as follows: Section 2 will describe the shop environment and multi-cell configurations considered in this study. Section 3 will present the experimental design, while Section 4 will discuss the results of this study. Finally, Section 5 presents the conclusions and managerial implications.

2. SHOP ENVIRONMENT AND MULTI-CELL CONFIGURATIONS CONSIDERED

This section presents the model assumptions, the shop factors and the multi-cell configurations considered. The shop environment was modeled via computer simulation utilizing, Pascal-based, Delphi ® programming software (Osier *et al.* 1997). The model assumptions are:

- Jobs arrive dynamically based on a Poisson process so that the overall worker utilization averaged 80%. This is consistent with previous studies which have considered cell utilizations of 75% to 90% (e.g., Jensen 2000; Fuji *et al.* 2000). Each job was assigned a respective quantity based on a *Uniform* (50, 150) distribution and the due dates were set based on the TWK rule (Conway *et al.* 1967), as described in Section 3.3. Jobs were processed based on the earliest due date rule.
- There are five product families, requiring similar equipment and sequence-dependent setup times. The number of product families considered is well within the range of values used in previous research (e.g., Gupta *et al.* 2003, and Kim *et al.* 2003).
- Worker productivity is consistent regardless of the number of workers utilized. For example, if five workers complete 100 units in one hour, 10 workers will complete it in approximately 30 minutes. The production rate per family, per worker was modeled by *Uniform* (5, 15) distribution as this was well within the range of many of the observed systems. This approach has also been used by Liao and Ling (2003), and Koulamas and Kyrpasis (2004).
- Worker movement is modeled by *Uniform* (6, 24) distribution with an average move times of 15 minutes (Ruiz-Torres and Mahmoodi 2007). We attempted to minimize the number of worker movements as that is the case in most shops. For example, the workers were moved from one cell to another only if it resulted in additional on time job completions.
- The process of assigning jobs to flexible cells was aimed at balancing workload across the families while minimizing the setup times. A similar cell shop performed well in some instances in the case where the number of families was larger than the number of cells (Ruiz-Torres 2002).

2.1 Shop factors

We now describe the shop factors utilized to generate the various multi-cell configurations considered in this study.

2.1.1 Cell size (C)

The cell size factor is considered at two levels: *Normal Size* (NS) and *Small Size* (SS). The cell size relates to the baseline number of workers that are assigned to the cell. For normal size cells, the baseline number of workers is 10, while for small cells the baseline number of workers is 5. We considered five normal cells or 10 small cells, so the total number of workers assigned to the multi-cell production systems was kept at 50. In addition, each of the two cell sizes have different number of workers that can be added and a minimum number of workers that have to be assigned to the cell to insure effective operation. This is described in more detail in the next section.

2.1.2 Worker flexibility (W)

The worker flexibility factor is considered at two levels: *Non-Flexible* (NF) and *Flexible* (FL). This factor represents the ability of manufacturing cells to function with different number of workers and therefore represents a mechanism to vary the effective production rate of the cell. This is loosely related to the worker-to-machine ratio factor used in previous studies such as Jensen (2000). In the non-flexible case, the number of workers at a cell cannot deviate from the baseline. In the flexible case, the number of workers can vary 40% in both directions: in normal size cells the number of workers can range from six to 14, and in small cells, the number of workers can range from three to seven.

2.1.3 Shop type (T)

This factor considers the type of cellular manufacturing shop utilized to process jobs. Two cell shops are examined:

1. *Strict Cell (SC) Shop*, where each cell is dedicated to producing only one product family (i.e., switching to other product families is not allowed and thus major setups are never required). As illustrated in Figure 1, each family is assigned to only one cell in the case of normal size cells and to two cells in the case of small cells.

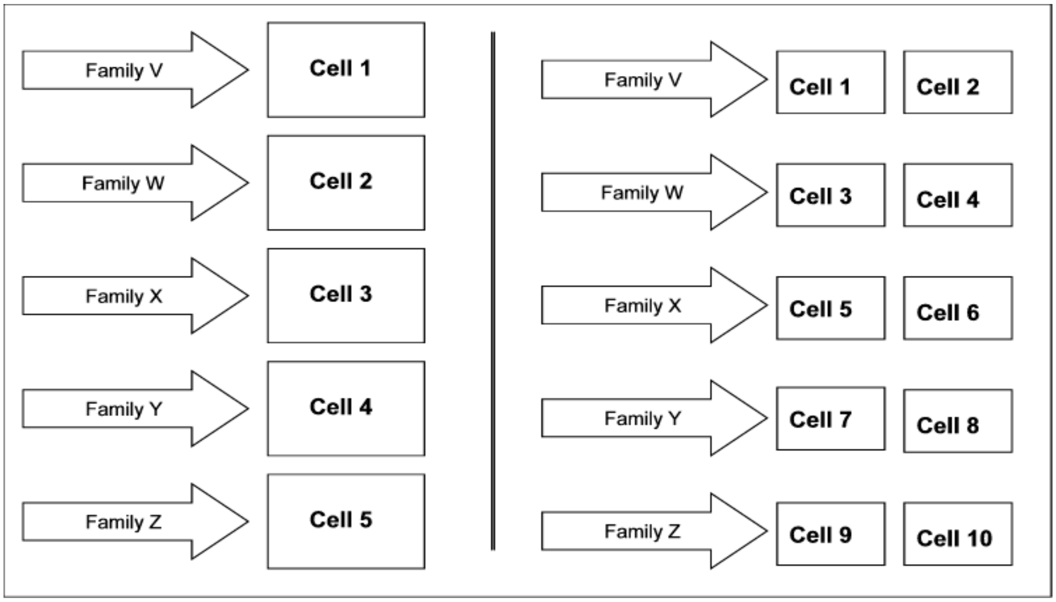

Figure1: Strict Cell Shop Type

2. *Flexible Cell (FC) Shop*, where each cell can produce multiple product families, as illustrated in Figure 2.

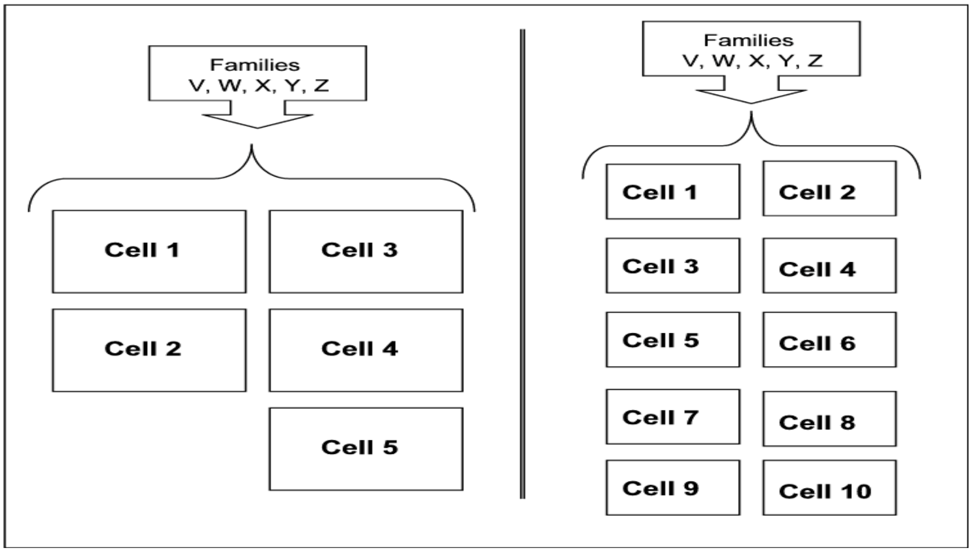

Figure 2: Flexible Cell Shop Type

2.2 Configurations examined

Eight multi-cell configurations generated from the three shop factors discussed are examined:

- *C1: NS-NF-SC - Normal Size Cell, Non-Flexible Workers, and Strict Cell Shop*
- *C2: NS-NF-FC - Normal Size Cell, Non-Flexible Workers, and Flexible Cell Shop*
- *C3: NS-FL-SC - Normal Size Cell, Flexible Workers, and Strict Cell Shop*
- *C4: NS-FL-FC - Normal Size Cell, Flexible Workers, and Flexible Cell Shop*
- *C5: SS-NF-SC - Small Size Cell, Non-Flexible Workers, and Strict Cell Shop*
- *C6: SS-NF-FC - Small Size Cell, Non-Flexible Workers, and Flexible Cell Shop*
- *C7: SS-FL-SC - Small Size Cell, Flexible Workers, and Strict Cell Shop*
- *C8: SS-FL-FC - Small Size Cell, Flexible Workers, and Flexible Cell Shop*

The first configuration is considered as the baseline and is used to experimentally set the shop utilization level at 80% and the due date tightness at levels discussed in Section 3.3.

3. EXPERIMENTAL DESIGN

This section describes the three experimental factors considered in the study: product mix balance, due date tightness, and setup-to-processing-time ratio. Each of these experimental factors is considered at three levels. Given that eight configurations are examined under each experimental condition, an 8 x 3^3 full factorial experiment was conducted. The first 500 jobs for each replication were discarded for system warm-up. Graphical analysis demonstrated that steady-state condition was reached after processing 200-400 jobs. The performance measures were tracked for the next 10,000 jobs. For each experimental condition, we performed 50 replications to ensure sufficient statistical precision.

The average percentage of jobs tardy was selected as the primary performance measure as it reflects the concern of the majority of managers interviewed during our site visits. The average flowtime was also considered as a performance measure due to its significance as an efficiency-oriented performance measure. We now discuss each experimental factor in more detail.

3.1 Setup-to-processing-time ratio (*S*) factor

Previous research has demonstrated that setup times play a significant role on the performance of cellular systems (e.g., Mahmoodi *et al.* 1990, Mahmoodi and Dooley 1991, Mahmoodi *et al.* 1992, Ruben *et al.* 1993, Suresh and Meredith 1994). When setup times are relatively low, the flexible cell shop has typically performed very well, while as setup times increase, strict cell shops have outperformed the flexible cell shops (Ruiz-Torres and Mahmoodi 2007). In this paper, the setup-to-processing-time ratio is considered at three levels: 0.5, and 1, and 1.5, consistent with Ruben *et al.* (1993) and Ponnambalam *et al.* (1999). These levels allow the evaluation of different multi-cell systems when the setup time is a major as well as, a minor factor relative to processing time. At each setup event, the actual setup time was generated using a second-order Erlang distribution as in Ruben *et al.* (1993).

3.2 Product mix balance (*B*) factor

Product mix variability is a predominant environmental factor in manufacturing today. As customer preferences change, so do the production requirements. The product mix in many of the observed environments changed often, and managers had to quickly adjust cell capacity to meet customer needs. This factor has been investigated in previous research including Ruben *et al.* (1993), Davis and Mabert (2000), and Fuji *et al.* (2000). Previous research has shown that shop performance is highly dependent on the product mix balance. For example, in cases of minor product mix unbalances, strict cell shops often outperformed flexible cell shops, while the opposite occurred in cases of moderate and extreme product mix unbalance (Ruiz-Torres and Mahmoodi 2007). We included this factor in our experiment due to its significance in previous research and the current reality in manufacturing environments.

The product mix balance factor was modeled by characterizing each of the five families as either dominant or non-dominant. The two dominant families received the largest percentage of the demand while the three non-dominant families received smaller percentage of the demand. Similar to previous studies (e.g., Ruben *et al.* 1993), each of the dominant and non-dominant families received an equal proportion of the percentage allocated demand, as illustrated below.

Factor Levels	Dominant Family Total	Each Dom. Fam.	Each Non-Dom. Fam.
Minor Unbalance	50%	25%	16.7%
Moderate Unbalance	65%	32.5%	11.6%
Extreme Unbalance	80%	40%	6.67%

Family dominance changes over time. The time between changes was modeled by a Poisson variable with a mean of 40 shifts. This factor serves to model dynamic changes in customer preferences.

3.3 Due date tightness (*D*) factor

Due date tightness is an important factor influencing the possible effectiveness of a production system. Due date tightness relates to the amount of slack jobs have in relation to their expected processing time. The job due dates were set based on the TWK rule (Conway *et al.* 1967). Three levels of this factor were considered: loose, intermediate, and tight resulting in 35%, 45% and 55% of jobs tardy under the baseline condition, respectively. These levels are similar to the values used in Jensen (2000) and Ponnabalam *et al.* (1999).

4. ANALYSIS OF THE RESULTS

Analysis of Variance (ANOVA) was conducted using the MINITAB commercial software package to determine the significance of the main and interaction effects of the shop and experimental factors (Ryan *et al.* 2000). Table 1 presents the ANOVA results. For brevity, only the main effects and two-way interactions are presented (the higher-order interactions provided no additional insights). The assumption of homogeneity of variances was examined using Levene's test (Sheskin, 1997). Sidak's Multiple Pairwise Comparisons were also performed for each performance measure in order to determine if the performance of multi-cell configurations were significantly different under various experimental conditions (Sidak 1967). An experiment-wise significance level of 95% (i.e., *alpha* = 0.05) was assumed. Thus, due to multiple comparisons, significant terms will have a p-value of 0.05 / 28 = 0.00178 or less. The results were analyzed on each performance measure separately.

Table 1. ANOVA Results.

		% of Jobs Tardy		*Average Flowtime*	
Source	*DF*	F	*P*	F	*P*
C	1	8,080.5	0.000	9.6	0.002
W	1	5,081.8	0.000	445.8	0.000
T	1	1,153.8	0.000	52000.0	0.000
B	2	273.4	0.000	16000.0	0.000
D	2	22,000.0	0.000	3.0	0.048
S	2	5,685.8	0.000	15.8	0.000
*C*W*	1	827.1	0.000	33.0	0.000
*C*T*	1	5,549.3	0.000	83.3	0.000
*C*B*	2	33.9	0.000	20.1	0.000
*C*D*	2	4,403.9	0.000	0.3	0.768
*C*S*	2	292.0	0.000	10.1	0.000
*W*T*	1	188.9	0.000	405.1	0.000
*W*B*	2	0.6	0.559	90.5	0.000
*W*D*	2	541.4	0.000	2.0	0.141
*W*S*	2	17.9	0.000	0.1	0.889
*T*B*	2	5,218.2	0.000	17000.0	0.000
*T*D*	2	443.3	0.000	0.2	0.838
*T*S*	2	5,712.6	0.000	4.0	0.019
*B*D*	4	34.4	0.000	0.0	0.999
*B*S*	4	54.9	0.000	0.1	0.989
*D*S*	4	25.5	0.000	1.2	0.315

4.1 Average percentage of jobs tardy

The ANOVA results indicate that all the main effects and 14 of the 15 two-way interactions are significant. The due date tightness (*D*) and cell size (*C*) factors are the most significant factors. The worker flexibility (*W*) and setup-to-processing-time ratio (*S*) factors were also highly significant, while the shop type (*T*) and product mix balance (*B*) factors had the lowest *F* values among the main effects. We discuss four of the most significant interaction effects in the following.

The interaction of cell size (*C*) and shop type (*T*) factors indicates that the performance of flexible cell shops is much more robust with respect to the cell size factor than that of the strict cell shops. Thus, while the performance of the flexible cell shops remained the same as the cell size decreased, the performance of the strict cell shops deteriorated significantly. This result extends the findings of Suresh (1992) by showing that as long as there exists some routing flexibility in the shop even the small cells can perform well. However, shops with no routing flexibility need to be large to function effectively.

The interaction effect of due date tightness (*D*) and cell size (*C*) factors, indicates that the performance of normal size cells is much more robust with respect to due date tightness factor than the performance of small cells. While the cell size did not impact the shop performance under loose due dates, the performance of the small cells deteriorated much more rapidly as due dates became tighter. This can be attributed to the fact that the increased routing flexibility offered by larger cells is useful when the shop faces more constraints such as tighter due dates.

The interaction effects of product mix balance (*B*) and shop type (*T*) factors indicates that as the product mix balance changed from minor to extreme level, the performance of the flexible shops improved, while the performance of the strict cell shops deteriorated. This can be attributed to the fact that in the flexible cell shop product mix unbalance results in fewer setups, while in strict cell shops some cells become highly underutilized while others highly overutilized, resulting in many tardy jobs. The interaction effect of shop type (*T*) and setup-to-processing-time factors indicates an expected relationship: the performance of strict cell shops are very robust with respect to the setup factor while the performance of flexible cell shops deteriorate rapidly as setup times increase. This result in consistent with the results of a previous study (i.e., Ruiz-Torres and Mahmoodi 2007) which concluded that flexible cell shops perform best when setup times are low, while the strict cell shops perform best when setup times are high.

A summary of the average percentage of jobs tardy is presented in Table 2. Note that while the strict cell shop (*SC)* configurations are not affected by setup (*S*) factor (since no setups are required), the results at similar levels of product mix balance (*B)* and due date tightness (*D)* factors are not exactly the same. This is due to the inherent randomness of the simulated environments and the fact that common random numbers are not utilized in this simulation study. Each simulation run uses different random numbers to generate job arrivals, processing rates, worker movement times, etc.

Table 3 compares the performance of the top three dominant configurations with the performance of the baseline configuration (i.e., *C1: NS-NF*-SC). The dominant configurations (i.e., *C3: NS-FL-SC*, *C4: NS-FL-FC*, and *C8: SS-FL-FC*) outperform all others configurations under the experimental conditions considered. Note that the improvement of each of the dominant configurations over the baseline configuration is presented and the best performing configuration(s) is determined based on Sidak's Multiple Pairwise Comparisons (blank cells represent less than 1% improvement or performance deterioration). Results in bold indicate the most significant improvements. The three dominant configurations represent a change from the baseline configuration in the following manner: utilize flexible workers (*C3: NS-FL-SC*), utilize flexible workers and flexible cell shops (*C4: NS-FL-FC)*, and utilize small cells, flexible workers and flexible cell shops (*C8: SS-FL-FC)*. The only two configurations that did not outperform the baseline configuration under any experimental conditions were the *C5: SS-NF-SC* and *C7: SS-FL-SC* configurations, indicating a design that combines small cells and a strict cell shop is not effective on the average percentage of jobs tardy criterion.

Table 2. Overall Results for the Percentage of Jobs Tardy

S	*B*	*D*	*C1: NS-NF-SC*	*C2: NS-NF-FC*	*C3: NS-FL-SC*	*C4: NS-FL-FC*	*C5: SS-NF-SC*	*C6: SS-NF-FC*	*C7: SS-FL-SC*	*C8: SS-FL-FC*
0.5	*Minor*	*Loose*	35.0	33.6	33.2	30.9	47.9	30.4	42.3	26.4
		Intermediate	45.4	45.3	41.9	40.9	69.8	47.8	59.4	37.2
		Tight	55.2	51.5	46.9	42.3	87.0	93.0	74.3	52.3
	Moderate	*Loose*	45.0	31.3	42.0	28.3	56.7	29.1	51.5	26.0
		Intermediate	54.3	43.2	51.3	39.4	75.3	47.0	67.0	38.3
		Tight	60.7	46.2	53.2	39.0	89.7	92.6	78.7	48.3
	Extreme	*Loose*	57.8	28.8	53.8	26.6	67.7	27.4	62.6	25.2
		Intermediate	66.4	38.1	60.9	34.2	84.9	44.2	76.8	34.7
		Tight	69.9	41.4	62.0	35.8	96.4	85.4	86.9	46.1
1	*Minor*	*Loose*	34.5	58.4	32.9	56.5	47.9	41.0	42.1	35.6
		Intermediate	45.7	70.0	41.9	65.0	68.2	65.6	59.7	52.9
		Tight	54.6	75.9	46.4	67.8	86.1	94.8	73.6	80.8
	Moderate	*Loose*	44.9	54.1	42.4	47.2	56.5	38.2	51.4	33.1
		Intermediate	54.4	64.4	50.5	60.4	75.3	63.6	66.9	49.0
		Tight	60.6	69.0	52.9	60.5	89.5	93.7	78.9	75.9
	Extreme	*Loose*	57.7	42.3	53.9	38.3	67.5	35.3	62.1	31.3
		Intermediate	66.0	53.4	61.4	48.4	84.2	55.8	77.5	44.0
		Tight	70.2	59.8	62.2	51.6	89.5	91.4	87.7	70.3
1.5	*Minor*	*Loose*	34.8	80.4	33.2	76.4	48.3	55.0	41.8	45.5
		Intermediate	45.6	88.3	41.7	86.0	69.1	80.4	60.2	67.0
		Tight	55.1	89.1	46.5	84.6	86.8	97.0	73.5	89.9
	Moderate	*Loose*	44.8	70.9	42.2	67.7	57.1	50.3	51.3	43.9
		Intermediate	54.2	80.0	51.1	76.0	75.0	75.7	67.3	63.6
		Tight	61.1	81.4	53.1	77.0	89.7	95.5	79.3	86.0

	Extreme	*Loose*	57.7	57.3	54.0	52.1	67.3	43.5	61.8	37.6
		Intermediate	66.2	66.0	61.5	64.2	84.1	68.9	77.0	55.6
		Tight	71.0	71.6	62.1	65.6	92.3	94.6	87.2	80.1

Table 3. Percentage of Jobs Tardy Performance Improvements Over the Baseline (NS-NF-SC) and Dominant Configurations

S	*B*	*D*	*C3: NS-FL-SC*	*C4: NS-FL-FC*	*C8: SS-FL-FC*	*Dominant Configuration(s) (Sidak's Test)*
0.5	*Minor*	*Loose*	5%	12%	**25%**	*C8*
		Intermediate	8%	10%	**18%**	*C8*
		Tight	15%	**23%**	5%	*C4*
	Moderate	*Loose*	7%	37%	**42%**	*C8*
		Intermediate	6%	**27%**	**29%**	*C8,C4*
		Tight	12%	**36%**	20%	*C4*
	Extreme	*Loose*	7%	54%	**56%**	*C8*
		Intermediate	8%	**48%**	**48%**	*C4,C8*
		Tight	11%	**49%**	34%	*C4*
1	*Minor*	*Loose*	**5%**			*C3*
		Intermediate	**8%**			*C3*
		Tight	**15%**			*C3*
	Moderate	*Loose*	6%		**26%**	*C8*
		Intermediate	7%		**10%**	*C8*
		Tight	**13%**			*C3*
	Extreme	*Loose*	7%	34%	**46%**	*C8*
		Intermediate	7%	27%	**33%**	*C8*
		Tight	11%	**26%**		*C4*
1.5	*Minor*	*Loose*	**4%**			*C3*
		Intermediate	**9%**			*C3*
		Tight	**16%**			*C3*
	Moderate	*Loose*	**6%**		2%	*C3*
		Intermediate	**6%**			*C3*
		Tight	**13%**			*C3*
	Extreme	*Loose*	6%	10%	**35%**	*C8*
		Intermediate	7%	3%	**16%**	*C8*
		Tight	**13%**	8%		*C3*

The *C3: NS-FL-SC* configuration outperformed the baseline configuration under all experimental conditions, indicating having flexible workers will always improve performance. This configuration outperformed all others in 11 of the 27 experimental conditions and was the best performing configuration when setups were high and the product mix balance was at minor or moderate levels. The *C4: NS-FL-FC* configuration outperformed the baseline configuration in 15 of the 27 cases, and was the best performing configuration in six cases (two of those tied with the *C8: SS-FL-FC* configuration). The performance of this configuration was the best when setups were low and the due dates were tight. Finally, the *C8: SS-FL-FC* configuration was the best performing in 12 cases, when due dates were set at loose or intermediate levels. The performance of this configuration was also highly dependent on setups, as it generally performed better at lower setup levels. The performance of the different configurations again indicated that the flexible and strict cell shops are adversely impacted by high setup times and extreme product mix unbalance, respectively.

The effect of the due date tightness factor on the performance of the three dominant as well as the baseline configurations clearly demonstrates that the performance of the *C8: SS-FL-FC* configuration is not as robust with respect to the due date tightness factor as the other configurations. This indicates that the performance of small cells is not as robust with respect to the due date tightness factor as the larger cells (which can be attributed to the large increase in the number of worker reallocations as due dates become tighter). Worker reallocations are higher in the *C8: SC-FL-*FC configuration and increased rapidly as due dates became tighter, responding to the need for additional workers in order to complete jobs by their due dates. This indicates an implementation problem for the *C8: SC-FL-*FC configuration when the due dates are tight. Note that the *C8: SS-FL-FC* configuration was only dominant when due date tightness was at loose or intermediate levels.

4.2 Average Flow-time

The average flow-time results are presented in Table 4. The ANOVA results indicate that all the main effects and nine two-way interactions are significant. The shop type (*T*) and the product mix balance (*B*) factors are clearly the dominant effects. The interaction of product mix balance (*B*) and shop type (*T*) factors indicates a rapid performance deterioration of strict cell shops as the product mix becomes more unbalanced. On the other hand, the performance of flexible cell shops is very robust with respect to the product mix balance factor. This result is a bit more pronounced than the average percentage of jobs tardy results.

Table 4. Overall Results for the Average Flow-time

S	*B*	*D*	*C1: NS-NF-SC*	*C2: NS-NF-FC*	*C3: NS-FL-SC*	*C4: NS-FL-FC*	*C5: SS-NF-SC*	*C6: SS-NF-FC*	*C7: SS-FL-SC*	*C8: SS-FL-FC*
0.5	*Minor*	*Loose*	17.6	4.6	14.7	4.4	19.2	5.2	16.2	5.1
		Intermediate	17.6	4.8	13.9	4.5	21.1	5.2	15.4	4.9
		Tight	19.0	4.6	13.2	4.2	19.6	5.3	18.3	4.5
	Moderate	*Loose*	103.2	4.4	78.1	4.1	108.9	5.2	91.2	5.1
		Intermediate	102.6	4.6	87.8	4.4	101.7	5.2	90.2	5.0
		Tight	105.1	4.3	82.5	4.0	103.1	5.3	96.3	4.3
	Extreme	*Loose*	230.2	4.1	191.5	3.9	239.1	5.0	208.0	5.0
		Intermediate	219.3	4.1	188.1	3.8	237.3	5.1	205.8	4.8
		Tight	237.1	4.0	179.1	3.9	248.4	5.1	218.0	4.3
1	*Minor*	*Loose*	17.7	8.5	14.2	8.7	20.9	6.3	15.1	6.2
		Intermediate	20.9	8.6	13.5	8.0	18.0	6.2	16.6	5.9
		Tight	18.2	8.9	12.1	7.7	17.5	6.2	18.5	5.6
	Moderate	*Loose*	103.3	8.3	79.4	7.1	108.0	6.0	88.3	5.9
		Intermediate	109.4	7.9	79.5	7.7	101.6	6.3	90.5	5.7
		Tight	106.6	7.5	78.0	6.5	102.0	6.2	92.9	5.4
	Extreme	*Loose*	232.7	6.3	188.7	5.7	240.3	5.9	201.8	5.8
		Intermediate	231.4	6.2	192.5	5.8	234.0	5.7	214.3	5.4
		Tight	230.3	6.3	187.1	5.5	229.1	6.0	214.4	5.2
1.5	*Minor*	*Loose*	19.6	16.3	14.3	15.0	19.6	7.9	14.4	7.2
		Intermediate	18.8	16.4	13.1	15.4	20.0	8.0	16.6	7.3
		Tight	19.6	16.9	12.4	15.5	18.7	7.6	15.3	6.9
	Moderate	*Loose*	100.2	13.0	86.4	12.4	107.4	7.3	93.7	7.2
		Intermediate	108.0	13.3	84.7	12.0	102.3	7.3	99.0	6.9
		Tight	112.2	13.1	78.3	12.2	103.2	7.4	92.7	6.5
	Extreme	*Loose*	227.8	9.5	194.2	8.6	242.5	6.7	213.3	6.5
		Intermediate	232.1	8.9	202.9	9.2	239.3	6.7	217.9	6.4
		Tight	250.4	9.6	188.8	8.7	223.4	6.8	204.9	6.0

The interaction effect of worker flexibility (*W*) and shop type (*T*) factors indicates that while in the flexible cell shops the worker flexibility factor does not impact the performance, in the strict cell shops worker flexibility improves the performance. This demonstrates the importance of having some type of flexibility in the strict cell shops to achieve good performance.

Table 5 compares the performance of the top four dominant configurations with that of the baseline configuration. The dominant configurations (i.e., *C2: NS-NF-FC, C4: NS-FL-FC, C6: SS-NF-FC* and *C8: SS-FL-FC*) outperform all other configurations under the experimental conditions considered. The improvement of each of the dominant configurations over the baseline configuration is presented and the best performing configuration(s) is determined based on Sidak's Multiple Comparisons (blank cells represent less than 1% improvement or performance deterioration). Results in bold indicate the most significant improvements. The four dominant configurations represent a change from the baseline configuration in the following manner: utilize flexible cell shops (*C2: NS-NF-FC)*, utilize flexible workers and flexible cell shops (*C4: NS-FL-FC*), utilize small cells and flexible cell shops (*C6: SS-NF-FC*), and utilize small cells, flexible workers and flexible cell shops (*C8: SS-FL-FC*). This demonstrates the superior performance of flexible cell shops compared to strict cell shops, as none of the dominant configurations utilized a strict cell shop. Note that all the dominant configurations outperformed the baseline configuration under some experimental conditions.

Table 5. Average flow-time Performance Improvements over the Baseline (NS-NF-SC) and Dominant Configurations

S	*B*	*D*	*C2: NS-NF-FC*	*C4: NS-FL-FC*	*C6: SS-NF-FC*	*C8: SS-FL-FC*	*Dominant Configuration(s) (Sidak's Test)*
0.5	*Minor*	*Loose*	**74%**	**75%**	**70%**	**71%**	*C4, C2, C8, C6*
		Intermediate	**73%**	**75%**	**70%**	**72%**	*C4, C2, C8, C6*
		Tight	**76%**	**78%**	**72%**	**77%**	*C4, C8, C2, C6*
	Moderate	*Loose*	**96%**	**96%**	**95%**	**95%**	*C4, C2, C8, C6*
		Intermediate	**96%**	**96%**	**95%**	**95%**	*C4, C2, C8, C6*
		Tight	**96%**	**96%**	**95%**	**96%**	*C4, C2, C8, C6*
	Extreme	*Loose*	**98%**	**98%**	**98%**	**98%**	*C4, C2, C8, C6*
		Intermediate	**98%**	**98%**	**98%**	**98%**	*C4, C2, C8, C6*
		Tight	**98%**	**98%**	**98%**	**98%**	*C4, C2, C8, C6*
1	*Minor*	*Loose*	52%	51%	**65%**	**65%**	*C8, C6*
		Intermediate	59%	62%	**70%**	**72%**	*C8, C6*
		Tight	51%	58%	**66%**	**69%**	*C8, C6*
	Moderate	*Loose*	**92%**	**93%**	**94%**	**94%**	*C8, C6, C4, C2*
		Intermediate	**93%**	**93%**	**94%**	**95%**	*C8, C6, C4, C2*
		Tight	93%	94%	94%	**95%**	*C8, C6, C4, C2*
	Extreme	*Loose*	**97%**	**98%**	**97%**	**98%**	*C4, C8, C6, C2*
		Intermediate	**97%**	**98%**	**98%**	**98%**	*C8, C6, C4, C2*
		Tight	**97%**	**98%**	**97%**	**98%**	*C8, C4, C6, C2*
1.5	*Minor*	*Loose*	17%	23%	**60%**	**63%**	*C8, C6*
		Intermediate	13%	18%	**58%**	**61%**	*C8, C6*
		Tight	14%	21%	**61%**	**65%**	*C8, C6*
	Moderate	*Loose*	**87%**	**88%**	**93%**	**93%**	*C8, C6, C4, C2*
		Intermediate	**88%**	**89%**	**93%**	**94%**	*C8, C6, C4, C2*
		Tight	**88%**	**89%**	**93%**	**94%**	*C8, C6, C4, C2*
	Extreme	*Loose*	**96%**	**96%**	**97%**	**97%**	*C8, C6, C4, C2*
		Intermediate	**96%**	**96%**	**97%**	**97%**	*C8, C6, C2, C4*
		Tight	**96%**	**97%**	**97%**	**98%**	*C8, C6, C4, C2*

The *C6: SS-NF-FC* and *C8: SS-FL-FC* configurations were the dominant configurations under all experimental conditions. The *C2: NS-NF-FC* and *C4: NS-FL-FC* configurations were the dominant configurations under all experimental conditions, except when product mix unbalance was minor and setup factor was at medium or high levels. This indicates the effectiveness of small cells under minor product mix unbalance and medium or high setup levels compared to larger cells. This can be attributed to the fact that the increased routing flexibility provided by the larger cells is not necessary when the product mix unbalance is minor. Furthermore, the lack of a need to perform setups in strict cell shops is more advantageous when setup times are at medium or high levels.

5. CONCLUSIONS AND MANAGERIAL IMPLICATIONS

The main objective of this research was to investigate the performance of alternative multi-cell configurations in an environment where several product families with variable demand are produced. Altering the cell size, the flexibility of workers assigned to the cells, and the shop type generated the different configurations. The cell size decision is particularly critical as it is typically linked to many other key decisions. The only previous research that considered cell size as an experimental factor (i.e., Suresh 1992) has shown that larger cells with some amount of routing flexibility perform better than excessively partitioned systems. The expectations of the researchers were that all of the shop and experimental factors have a significant impact on performance, but the nature of these effects was not known. The dominant configurations across both measures of performance are presented in Table 6. The results of our experiments can be summarized as following:

Table 6. Configurations in the Dominant Set Across Both Performance Measures

		S		
B	*D*	0.5	1.0	1.5
Minor	*Loose*	*C8: SS-FL-FC*		
	Intermediate	*C8: SS-FL-FC*		
	Tight	*C4: NS-FL-FC*		
Moderate	*Loose*	*C8: SS-FL-FC*	*C8: SS-FL-FC*	
	Intermediate	*C4: NS-FL-FC* *C8: SS-FL-FC*	*C8: SS-FL-FC*	
	Tight	*C4: NS-FL-FC*		
Extreme	*Loose*	*C8: SS-FL-FC*	*C8: SS-FL-FC*	*C8: SS-FL-FC*
	Intermediate	*C4: NS-FL-FC* *C8: SS-FL-FC*	*C8: SS-FL-FC*	*C8: SS-FL-FC*
	Tight	*C4: NS-FL-FC*	*C4: NS-FL-FC*	

- Cell size matters in configuration decisions: Multiple small cells provided better performance under low setup times and loose-to-moderate due date tightness levels, due to their ability to process a variety of jobs simultaneously. On the other hand, larger cells performed better under high setup conditions as well as low setup conditions and tight due dates. Furthermore, the performance of larger cells was more robust with respect to the due date tightness factor than the performance of small cells. The small cells only performed well when flexible cell shops were utilized, which demonstrates that as long as some routing flexibility exists even the small cell shops can perform well. However, shops with no routing flexibility need to be larger to perform effectively. This is especially true when the shops face more constraints such as tighter due dates and extreme product mix unbalance. Thus, a design that combines small cells and a strict cell shop is not effective.
- The choice of shop type is driven by multiple factors: The performance of different shop types are affected by all the experimental factors, although setup-to-processing-time ratio factor was the most important. Strict cell shops performed well when setup times were high while the flexible cell shops performed well when setup times were low. Therefore, the cell configuration decision (and the design/re-design of a cell system) must carefully consider the existing setup times. Furthermore, the performance of flexible cell shops was much more robust with respect to the product mix balance and cell size factors than that of the strict cell shops. Thus, the shop environment as well as the cell size should be carefully considered when making the shop type decision.
- Flexible workers outperform non-flexible workers: Everything being equal, the performance of configurations with flexible workers was superior to those of non-flexible workers in almost every instance. As long as the time needed for worker reallocation is small, the benefit of workers moving to complete jobs by their due dates is very beneficial. The number of worker reallocations may require different approaches to shop management; as the number of reallocations increase, more managerial control is required, making some of the configurations difficult to implement (e.g., *C8: SC-FL-FC* configuration when the due dates are tight).

When designing a multi-cell production system many considerations and decisions need to be made. This paper provided many insights by examining the performance of a number of multi-cell configurations, under a variety of experimental conditions. Future research directions include the consideration of other production resources (e.g., machines) in the cell size decisions. Also, the analysis of environments where the cell size is a function of the product demand, and therefore large cells are dedicated to high volume products, and small cells are dedicated to low volume products would be interesting. Finally, the analysis of flow shops with parallel cells at each stage of the shop (a case observed in industry and of increased planning complexity) would require further investigation.

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