A Simulation Analysis of the Impact of Family Configuration on Virtual Cellular Manufacturing

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Abstract:

Past research has shown that it is possible to simultaneously achieve the setup efficiencies of traditional cellular manufacturing systems and the routing flexibility of a job shop by viewing cells not as permanent, physical structures, but as temporary, `virtual' entities. This research demonstrates that the advantages of virtual manufacturing cells can be obtained over a range of part family configurations. In particular, virtual cellular manufacturing is robust to changes in the number and size of families being processed. Further, the research shows that the benefits can be obtained under setup conditions impartial to a family-oriented part environment.

1. Introduction

Manufacturers in batch production environments continue to be faced with a dilemma regarding which shop configuration to use when part mix is characterized by the presence of distinct part families. Whereas job shops offer a high degree of routing flexibility, they are inefficient with respect to setup efficiency. Conversely, group technology based cellular manufacturing systems exhibit a high degree of setup efficiency, but severely constrain routing flexibility. Flexible manufacturing systems provide an alternative when setup times are short, but the complex, automated production systems required come at significant expense.

Another option is to view manufacturing cells from a different perspective. The underlying intent of manufacturing cells is twofold. First, to capitalize on the processing similarities of jobs, primarily with respect to setups, and second to permanently dedicate equipment accordingly to simplify material handling and shop floor control. However, it is not necessary nor, according to the plethora of evidence, is it always desirable, for both of these objectives to be fulfilled. Based on comparisons of cellular layouts and process layouts with and without permanent machine dedication, Flynn and Jacobs (1987) concluded that permanent machine dedication has a significant, negative effect on shop performance. Layout, in contrast, is of only secondary importance in explaining differences in shop performance. If, however, the setup efficiencies of cellular layouts can be obtained without permanent machine dedication, there exists the potential to eliminate these differences. This can be accomplished by the use of `virtual' manufacturing cells. Allocating machines in a job shop based on family need so as to reduce setup frequency, but doing so on a temporary basis without physically changing the shop layout, offers the potential to resolve the apparent conflict described earlier between setup efficiency and routing flexibility. The result is a routing mechanism based on the processing needs of families similar to that of traditional cellular manufacturing systems. The difference, however, is that this mechanism can respond to changes in demand patterns. Cells are thus rapidly evolving structures that expand and contract based on current need.

In an earlier study it was shown that virtual cellular manufacturing performs better than traditional batch production methods over a range of shop conditions (Kannan and Ghosh 1995). However, two important questions were left unanswered that the current research addresses. First, how do changes in the configuration of families affect the benefits of virtual cells? With fewer families competing for a limited number of machines, the advantages of recognizing families and thus the benefits of virtual cells can be expected to decrease. Conversely, increasing the number of families might be expected to increase the benefits associated with a cellular configuration. Second, how important is a setup time in determining when to use virtual cells? As the magnitude of setup time decreases, the advantages of reducing setup frequency decrease. As this occurs, is there any advantage to be obtained from maintaining a cellular structure, or is a traditional job shop configuration equally effective?

2. Past research

Recent research abounds with examples of the limitations of traditional cellular manufacturing systems and in particular, the effects of permanent machine dedication. Flynn and Jacobs (1987) described a simulation study comparing cellular layouts with traditional process layouts and those containing dedicated machines. They demonstrated the adverse impact of permanent machine dedication even in process layouts as well as the poor overall performance of cellular layouts. Morris and Tersine (1990) showed that cellular layouts perform comparably to process layouts only under a limited set of conditions. These are conditions that provide significant opportunity for cellular layouts to exploit their inherent advantage with respect to setup efficiency and material handling. Suresh (1992) demonstrated analytically the negative impact of converting a process layout to a cellular layout with dedicated machines.

Although cellular layouts can outperform process layouts if they yield processing efficiencies, for example lower processing times (Suresh and Meredith, 1994), lower setup times or smaller lot sizes (Suresh 1992) or simultaneous processing of jobs on multiple machines (Shafer and Charnes 1993), attempts to overcome their inherent limitations, particularly with respect to routing flexibility and imbalances in cell utilization, have met with limited success. Group scheduling rules that exploit sequence dependencies within families improve shop performance (e.g. Ruben *et al.* 1993) but not to the extent that performance is comparable to that of a process layout (Flynn 1987). Routing parts outside their designated cells reduces problems of unbalanced cell utilization but at the expense of a loss in the material handling efficiency of a cellular layout. However, this does yield the potential for better performance than that of an equivalent process layout (Garza and Smunt 1991, Suresh 1992).

The concept of a cell as a temporary routing mechanism as opposed to a physical structure is not new (McLean *et al.* 1982). However, only recently has this concept been operationalized. Kannan and Ghosh (1995) described a mechanism by which idle machines in process departments are allocated to families as opposed to individual jobs. Priority is given to families with parts in the corresponding department queues but with no machines in the department assigned to them. Once a machine is assigned to a family, the family retains use of the machine until one of two conditions is met. Either no parts from the family remain in the corresponding department queue, or multiple machines in the department are assigned to the family while other families with parts in the queue have no machines in the department assigned to them. As machines from different process departments are assigned to families, routings develop through the shop similar to those of traditional manufacturing cells. However, these routings can change over time in response to changes in demand and machine availability. They showed that this virtual cellular configuration yields superior flow time, due date, and work-in-process performance than traditional cellular and job shop production methods over a range of setup time and part mix conditions. Two observations are of particular note. First, the configuration consistently outperforms traditional cellular layouts, despite the loss of the material handling efficiencies of a traditional cellular layout. Second, the configuration outperforms the more flexible job shop under setup time conditions not considered to be detrimental to the performance of the job shop.

In reaching these conclusions however, certain important issues concerning part mix and setup time conditions were not addressed. Although part mix variability was modelled by changing the relative demand for parts of each family, the configuration of families in terms of number and size was kept constant. Changing the number of families is an important factor when considering the use of family-based production methods (Wemmerlov 1993). A part population characterized by a single part family implies that only intra-family (minor) changes in setup that are short in duration are required when changing the part to be processed. This renders scheduling equivalent to the traditional job shop scheduling problem in which the focus in on sequencing individual jobs. When the number of families increases, however, the potential for more time consuming inter-family (major) setups increases. Attempts to reduce major setup frequency are more likely to be met with reductions in lost machine time and an increase in capacity. Similarly, changing family size changes the relative frequency of major versus minor setups. This may also affect the effectiveness of virtual cells relative to a traditional job shop. The observation that virtual cellular configurations outperformed the traditional job shop even when major setup time was not expected to compromise job shop performance raises the question of how large major setup time must be for family recognition to be warranted. Virtual cells introduce setup efficiency to job shops by changing the nature of scheduling decisions. No longer is scheduling a question of job dispatching. Instead decisions must be made regarding the allocation of machines to families. Different information is thus required to make effective scheduling decisions. This makes it important to recognize when different sets of information are of value. The current research addresses these issues by examining the performance of virtual cellular configurations compared to a job shop as part family configuration changes, and how this is affected by setup time conditions.

3. Experimental design

Four experimental factors are considered, shop configuration, setup time, number of part families, and family size.

3.1. *Shop configuration (shop)*

Three configurations are considered, a job shop, and two virtual cellular configurations. The job shop (JS) is a 30-machine, eight-department shop. Each department contains three or four identical machines. The virtual cellular configurations physically resemble the job shop. However, as described earlier, machines are allocated on a temporary basis to specific families. When an idle machine is to be allocated to a new family, one of two heuristics is used to select the family:

FAMS: The machine is allocated to the family with the lowest average slack per job.

MINM: The machine is allocated to the family requiring the fewest remaining machines to complete a cell that meets the processing requirements of all parts in the family. These heuristics are used not only because of their good performance in the study by Kannan and Ghosh (1995) but because of their different information requirements for making machine allocation decisions. Whereas FAMS considers only production activity in the department with the machine to allocate, MINM considers production activity in all other departments, allowing it to more fully recognize current shop conditions.

3.2. *Setup time (S/R)*

Three levels of major setup time are included. At the low level, major setup time is 10% of the mean operation processing time ($S/R = 0.1$), at the medium level, it is 20% ($S/R = 0.2$), and at the high level it is 30% ($S/R = 0.3$). In the study by Kannan and Ghosh (1995), the virtual cellular configurations were able to outperform the job shop even at an S/R ratio of 33.33%. The levels used in this study are chosen to facilitate a more detailed sensitivity analysis of the effects of setup time. The ratio of minor to major setup time is not an experimental factor but is fixed at one quarter (Flynn and Jacobs 1987).

3.3. *Number of families (NFAM)*

Three levels of this factor are considered. In the earlier study, parts belonged to one of five families. In this study, this represents an intermediate number of families. In addition, at the low level, parts belong to one of two families, and at the high level, there are a total of eight families. This set of factor levels is similar to that used by Wemmerlov (1993). With only two families, family mix more closely resembles that to be found in job shops with no family orientation. With eight families, the impact of families becomes more pronounced.

3.4. *Family size (FSIZE)*

Three family sizes are considered. Small families consist of four different parts. Medium sized families contain eight parts. This is similar to the average family size used in the earlier study. Large families contain twelve parts. The basis for different family sizes is similar to that used by Wemmerlov and Vakharia (1991).

4. Shop environment

The simulation environment is similar to that used by Kannan and Ghosh (1995). Part orders arrive according to a Poisson process with mean inter-arrival times established to yield average shop utilization of

Table 1. Treatment means for mean flow time.

			S/R = 0·1			*S/R* = 0·2			*S/R* = 0·3	
NFAM	*FSIZE*	FAMS	MINM	JS	FAMS	MINM	JS	FAMS	MINM	JS
	Small	192·36	196·88	201·56	189·68	196·25	199·53	189·89	196·72	199·73
Low	Medium	216·72	219·82	226·67	210·66	215·38	218·83	208·88	213·51	217·70
	Large	301·26	352·03	300·23	247·19	273·72	253·99	232·41	254·87	239·27
	Small	201·78	201·81	218·60	205·22	206·23	230·22	211·48	211·96	242·68
Intermediate	Medium	225·47	226·24	244·21	226·59	227·13	251·13	230·47	231·10	258·67
	Large	326·47	352·39	454·50	270·67	283·00	350·05	260·23	265·89	318·42
	Small	204·53	204·91	222·97	210·68	210·68	237·43	218·47	219·14	256·17
High	Medium	228·14	229·15	254·01	231·49	232·29	263·44	237·63	238·91	274·39
	Large	314·39	322·47	537·12	275·33	279·21	395·56	267·16	270·91	361·64

Table 2. Treatment means for σ_{FT}.

			S/R = 0·1			*S/R* = 0·2			*S/R* = 0·3	
NFAM	*FSIZE*	FAMS	MINM	JS	FAMS	MINM	JS	FAMS	MINM	JS
	Small	53·01	57·19	59·72	47·64	53·66	55·19	44·86	51·41	52·55
Low	Medium	70·29	74·43	79·55	64·14	69·50	72·24	61·03	65·30	69·58
	Large	146·58	192·50	136·59	94·62	126·17	98·91	79·79	106·59	83·55
	Small	60·03	60·97	69·63	55·35	56·76	73·38	53·62	55·01	76·66
Intermediate	Medium	77·39	78·69	88·98	72·53	73·52	89·83	70·29	71·54	89·44
	Large	171·78	231·20	250·46	108·36	128·21	165·81	93·31	100·09	133·83
	Small	59·73	63·72	70·95	56·98	59·56	76·40	55·23	58·21	83·83
High	Medium	77·82	79·61	94·52	73·50	74·53	95·52	71·89	73·89	97·82
	Large	151·67	169·11	317·84	108·75	118·68	196·47	97·42	103·62	162·80

Table 3. Treatment means for mean tardiness.

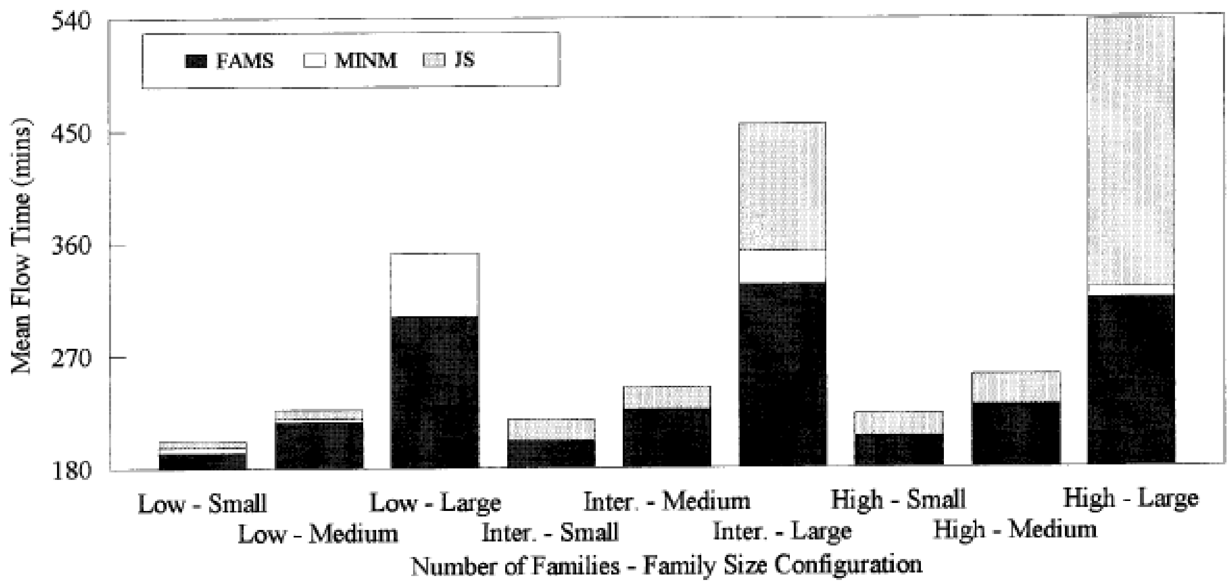
			S/R = 0·1			*S/R* = 0·2			*S/R* = 0·3	
NFAM	*FSIZE*	FAMS	MINM	JS	FAMS	MINM	JS	FAMS	MINM	JS
	Small	0·67	0·96	1·50	0·33	0·69	0·79	0·19	0·50	0·61
Low	Medium	1·56	2·02	3·03	0·84	1·37	1·73	0·44	0·73	1·30
	Large	40·42	75·90	36·04	9·02	21·42	10·41	3·62	10·77	4·34
	Small	1·63	1·80	3·55	1·05	1·27	5·08	0·89	1·12	6·81
Intermediate	Medium	2·69	3·16	5·57	1·84	2·16	6·41	1·53	1·85	6·38
	Large	59·24	89·90	149·26	17·22	29·57	62·13	8·87	13·92	35·13
	Small	1·42	2·36	4·27	1·19	1·79	5·51	0·91	1·62	10·09
High	Medium	2·96	3·82	8·39	2·21	2·77	8·64	1·79	2·64	10·05
	Large	43·89	52·74	219·47	15·86	20·46	93·79	8·82	12·29	61·91

80% in the job shop when the number of families and family size are five and eight, respectively. Parts require between three and five operations, no more than one of which occurs in the same process department. Processing times are normally distributed with a mean of 34.33 minutes and a standard deviation of 0.25 minutes. Due dates are set using the total work content method (Baker 1984) with an allowance of three. Parts are moved between machines at a rate of five miles per hour. Loading/unloading times are uniformly distributed in the interval (1,5) minutes. Minimum slack dispatching is used, though in the job shop, parts identical to those just completed are given priority.

Data was collected for three performance measures, the mean and standard deviation of flow time (σ_{FT}), and mean tardiness. For each of the 81 treatments (3 x 3 x 3 x 3), data was collected from 31 batches of 1000 jobs. Batch size was determined from pilot runs made to ensure batch independence and a normal distribution of batch means. The first batch was in each case truncated to eliminate initialization bias. Common random numbers were used to reduce variance. To maintain independence, one number stream was not synchronized (Mihram 1974). The simulation models were written using the SIMAN simulation language (Pegden 1987) and user-written FORTRAN subroutines.

Table 4. Tukey multiple comparison results.

		S/R = 0·1			S/R = 0·2			S/R = 0·3		
NFAM	*FSIZE*	MFT	σ_{FT}	MT	MFT	σ_{FT}	MT	MFT	σ_{FT}	MT
Low	Small	FAMS MINM JS	FAMS MINM JS	FAMS MINM JS	FAMS MINM JS	FAMS MINM JS	FANS MINM JS		FAMS MINM JS	FAMS MINM JS
	Medium	FAMS MINM JS	FAMS MINM JS		FAMS MINM JS				FAMS MINM JS	
	Large	JS FAMS MINM	JS FAMS MINM	JS FAMS MINM	FAMS JS MINM	FAMS JS MINM	FAMS JS MINM	FAMS JS MINM	FAMS JS MINM	FAMS JS MINM
Intermediate	Small		FAMS MINM JS	FAMS MINM JS		FAMS MINM JS				
	Medium		FAMS MINM JS							
	Large	FAMS NIMN JS	FAMS MINM JS	FAMS MINM JS	FAMS NIMN JS	FAMS MINM JS	FAMS MINM JS		FAMS MINM JS	
High	Small		FAMS MINM JS	FAMS MINM JS						
	Medium		FAMS MINM JS	FAMS MINM JS		FAMS MINM JS				
	Large									



Absence of bar indicates negligible difference between FAMS & MINM or FAMS & JS (Low - Large)

Figure 1. Mean flow time performance ($S/R = 0{\cdot}1$).

5. Results

Treatment means for the three performance measures are presented in Tables 1± 3. Analysis of variance was carried out for each of the measures. Given the presence of significant higher order interactions, interpretation of the significant main effects has little value. As an alternative, the data was analysed separately for each setup time condition using Tukey paired comparisons. For each level, Tukey multiple comparisons of treatment means for the shop configurations were made for each combination of the family configuration factors, *NFAM* and *FSIZE* (Table 4). This allows the impact of changes in family configuration to be more readily examined, as well as facilitating examination of the impact of setup time.

5.1. $S/R = 0.1$

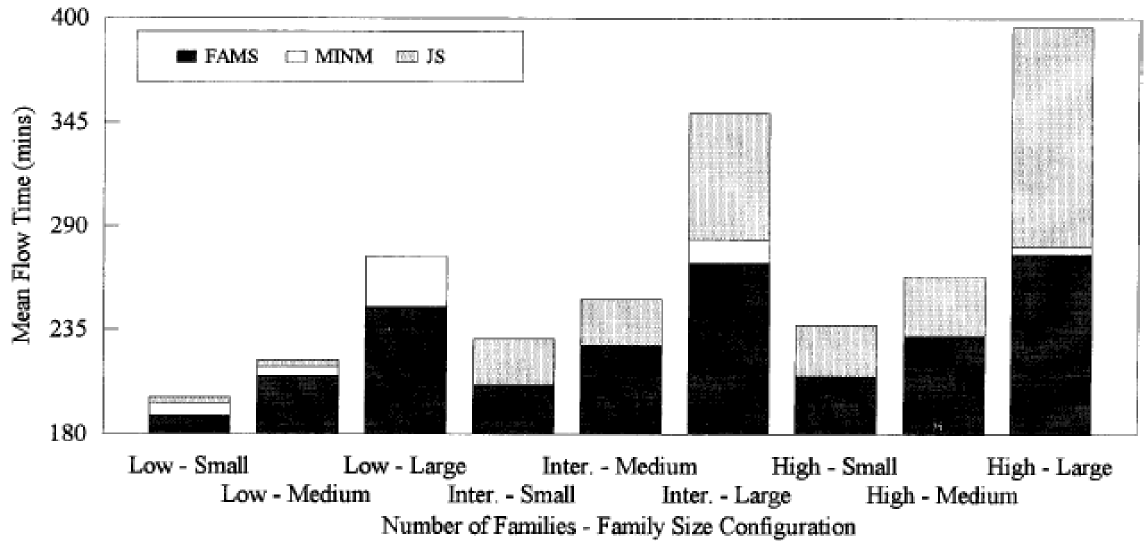
Even under the most benign setup time conditions, the use of virtual cellular configurations appear to yield some benefit. With only two part families, mean flow time is generally similar for all shop configurations, though when families are small, the two virtual cellular configurations show some improvement over the job shop (Figure 1). When family size increases, these two configurations always dominate. Virtual cellular con- figurations are less effective in improving flow time variance and due date performance. Only when *NFAM* is large and families have at least eight members do the virtual cellular configurations yield consistently lower values for σ_{FT} and mean tardiness. In addition, σ_{FT} is lower using these configurations when *NFAM* and *FSIZE* equal five and eight, respectively, and mean tardiness when *NFAM* and *FSIZE* equal five and twelve, respectively. Under other conditions, these configurations perform at least as well as the job shop or better depending on which configuration is used.

5.2. $S/R = 0.2$

As setup time increases, the advantages of the virtual cellular configurations become more apparent (Figure 2). For all performance measures, both FAMS and MINM outperform the job shop with few exceptions. These exceptions are that when there are two families, mean flow time and σ_{FT} are not consistently lower for FAMS and MINM. Whether virtual cellular manufacturing yields better performance depends on which implementation is used, but it always performs at least as well as the job shop. Due date performance is also indistinguishable for all three configurations when *NFAM* equals two.

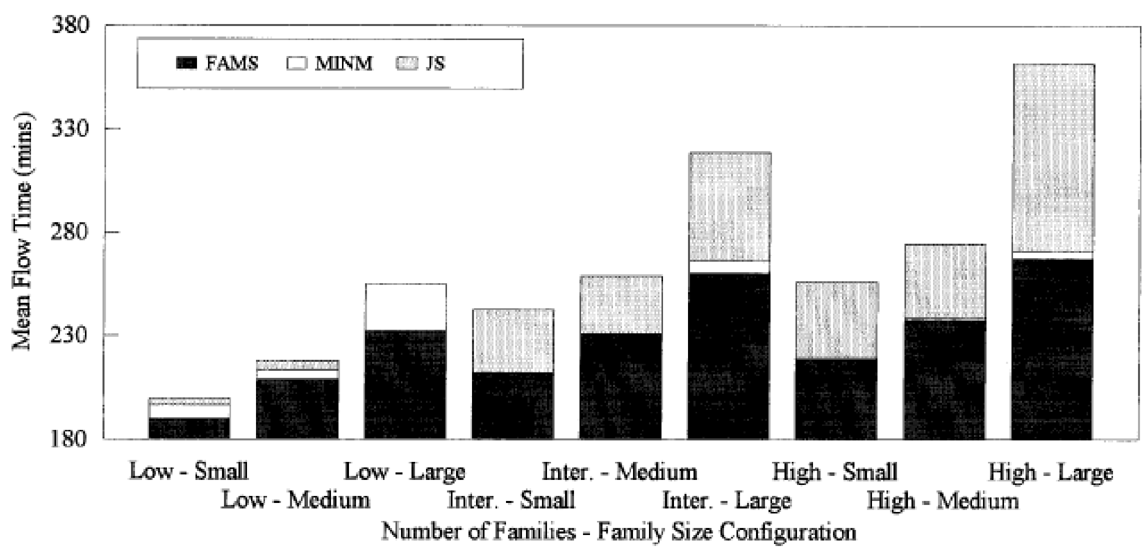
5.3. $S/R = 0.3$

The results for $S/R = 0.2$ largely repeat themselves when setup time increases further (Figure 3). The two virtual cellular configurations consistently perform



Absence of bar indicates negligible difference between FAMS & MINM or FAMS & JS (Low - Large)

Figure 2. Mean flow time performance ($S/R = 0{\cdot}2$).



Absence of bar indicates negligible difference between FAMS & MINM or FAMS & JS (Low - Large)

Figure 3. Mean flow time performance ($S/R = 0{\cdot}3$).

better when *NFAM* is either five or eight. However, even when *NFAM* equals two, they show greater potential to improve flow time performance than before. FAMS always outperforms the job shop when family size is four or eight. The job shop can in general only match the performance of MINM.

5.4. *Analysis of treatment means*

Additional information can be obtained by examining treatment means. With one exception, the number of families has a relatively modest impact on shop performance. For all measures, performance typically shows

Table 5. Percentage penalty in performance of job shop compared to average performance of virtual cellular configurations.

		MFT			σ_{FT}			MT		
	S/R	0·1	0·2	0·3	0·1	0·2	0·3	0·1	0·2	0·3
NFAM	*FSIZE*									
Low	Small	3·56	3·40	3·32	8·38	8·96	9·18	84·57	54·79	75·2
	Medium	3·85	2·73	3·08	9·95	8·11	10·15	71·12	56·32	123·2
	Large	−8·09	−2·48	−1·79	−19·43	−10·41	−10·35	−38·04	−31·59	−39·7
Intermediate	Small	8·33	11·91	14·63	15·09	30·91	41·15	106·89	337·52	577·7
	Medium	8·13	10·69	12·08	14·02	23·02	26·13	90·29	220·82	276·7
	Large	33·90	26·44	21·05	24·30	40·18	38·39	100·16	165·59	208·3
High	Small	8·91	21·69	17·08	14·94	31·12	47·79	126·04	268·66	697·5
	Medium	11·09	13·61	15·16	20·08	29·05	34·19	147·27	247·42	353·2
	Large	68·68	42·66	34·42	98·17	72·77	61·96	354·24	416·46	486·6

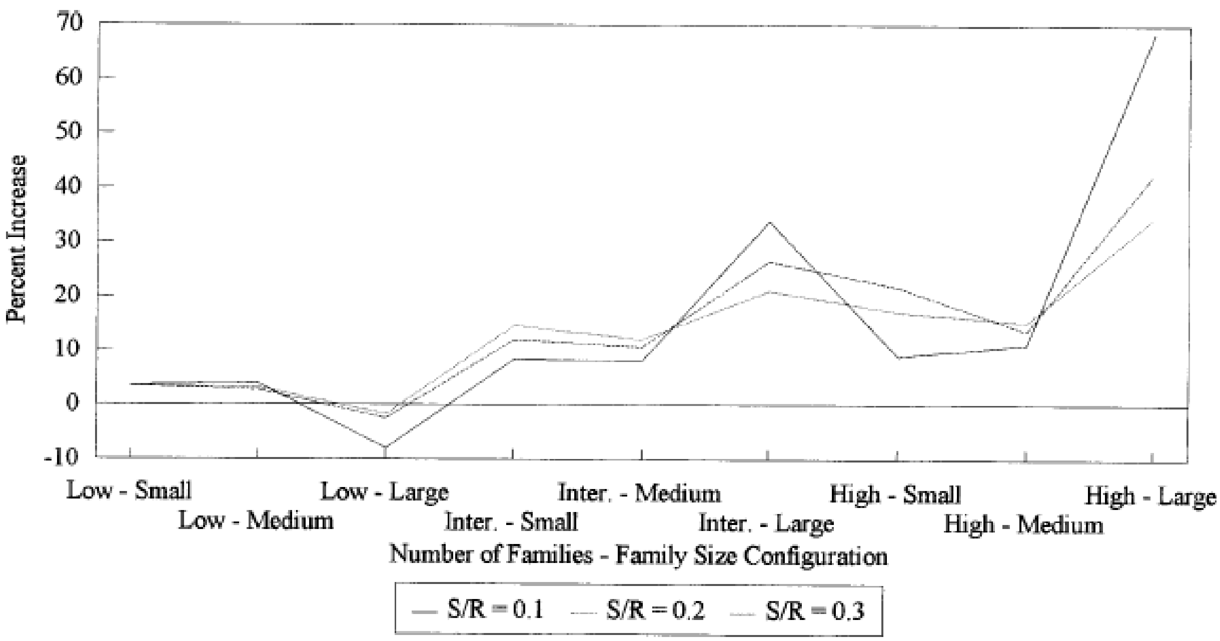


Figure 4. Percentage increase in mean flow time attributable to use of job shop.

only small deterioration as the number of families increases. The magnitude of this is generally greater for the job shop. However, within the job shop when family size is large, performance deteriorates dramatically as *NFAM* increases. As suggested by analyses of variance, family size has a significant impact on performance for all measures. As *FSIZE* increases, performance deteriorates, particularly as it goes from eight to twelve. This is again more noticeable in the case of the job shop.

To better illustrate the comparative performance of virtual cellular manufacturing with the job shop under the conditions examined, Table 5 shows the percentage decrease in shop performance yielded by the job shop compared to the average performance of the two virtual cellular configurations. This is represented graphically in Figures 4± 6. As is evident from Figures 1± 3, the performance of the two virtual cellular configurations is typically similar.

Even under low setup time conditions ($s / R = 0.1$), the job shop yields mean flow times that are from 3.56 to 11.09% higher than those of the virtual cellular configurations when family size is four or eight. Lower values correspond to smaller values of *NFAM*. However, when family size is twelve, this range goes from - 8.09 to 68.68% when the number of families increases from two to eight. In other words, the job shop performs relatively well when the number of families is small, which as discussed earlier is not unexpected. This, however, is largely due to the relatively poor performance of one of the virtual cellular configurations,

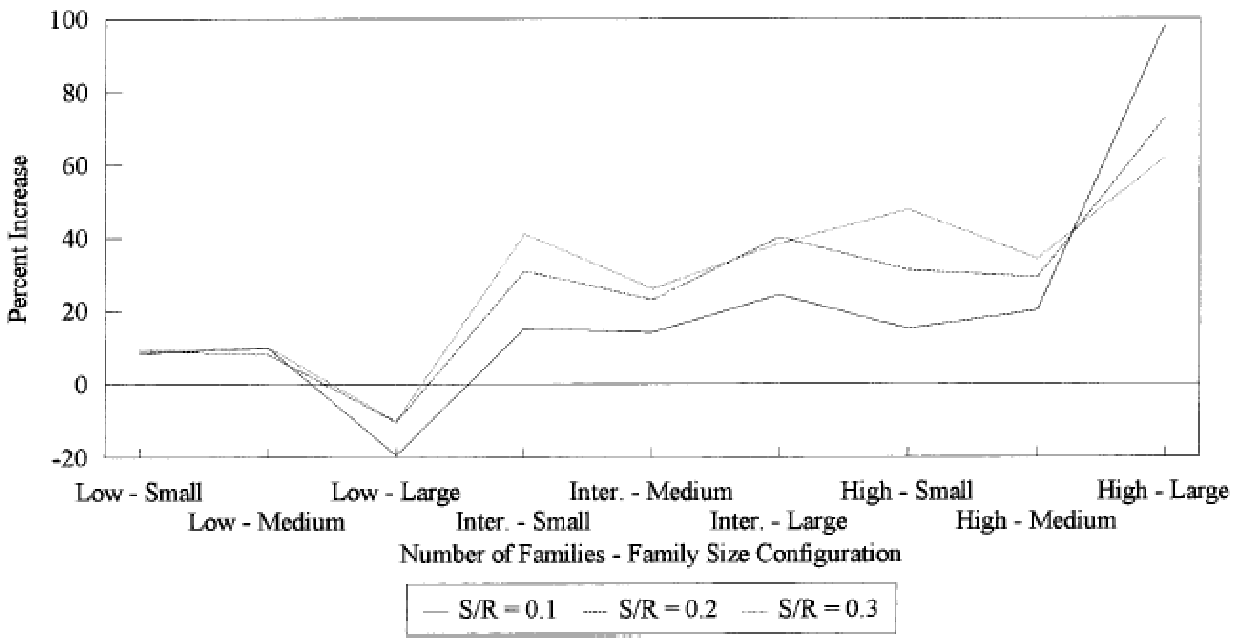


Figure 5. Percentage increase in standard deviation of flow time attributable to use of job shop.

MINM, under these conditions. As noticed previously, the greatest changes occur when family size goes from eight to twelve. As setup time increases, these trends repeat themselves. However, the relative disadvantage of the job shop typically increases as setup time increases except when family size is large and when the number of families is small. Similar observations are found with respect to σ FT. The magnitude of the job shop's disadvantage is, however, consistently larger and there is also a more pronounced disadvantage associated with increases in the number of families, particularly when NFAM goes from two to five. Without question, the greatest penalty associated with the job shop is with respect to due date performance. The job shop typically yields mean tardiness values that are between 70 and 150% higher than those of the virtual cellular configurations when setup time is low. As setup time increases, this worsens, particularly when the number of families is five or greater.

6. Discussion and implications for management

The results highlight several important observations. The first is the impact of setup time on shop performance. As previous research has suggested (Kannan and Ghosh 1995), large setup times favour the use of some form of cellular configuration. If setup time is large enough, even traditional cellular configurations perform better than job shops. What is evident from this study is that even when setup time is small in relation to processing time, recognizing part families when making machine allocation decisions has the potential to improve shop performance. When setup time is small, one might have expected the job shop to perform relatively better since the increased frequency of major setups is less of a handicap. However, the job shop performs at best, only as well as the virtual cellular configurations. This occurs when there are few families, when family recognition has the least potential for setup reduction. Once the number of families increases and competition between families for the limited machine resources increases, virtual cellular configurations, by virtue of their ability to efficiently re-distribute these resources given prevailing production needs, dominate. Not unexpectedly, this advantage increases as setup time increases.

The ability of virtual cellular configurations to allocate resources efficiently in response to changing demand patterns also explains their robustness to changes in the number of part families. This is in stark contrast to the job shop whose performance clearly deteriorates as *NFAM* increases. This is particularly important in a dynamic environment in which the number of families is subject to frequent change. Further, this creates less pressure to allocate new parts to existing families. This is a significant departure from traditional cellular systems, which cannot respond to changes in the

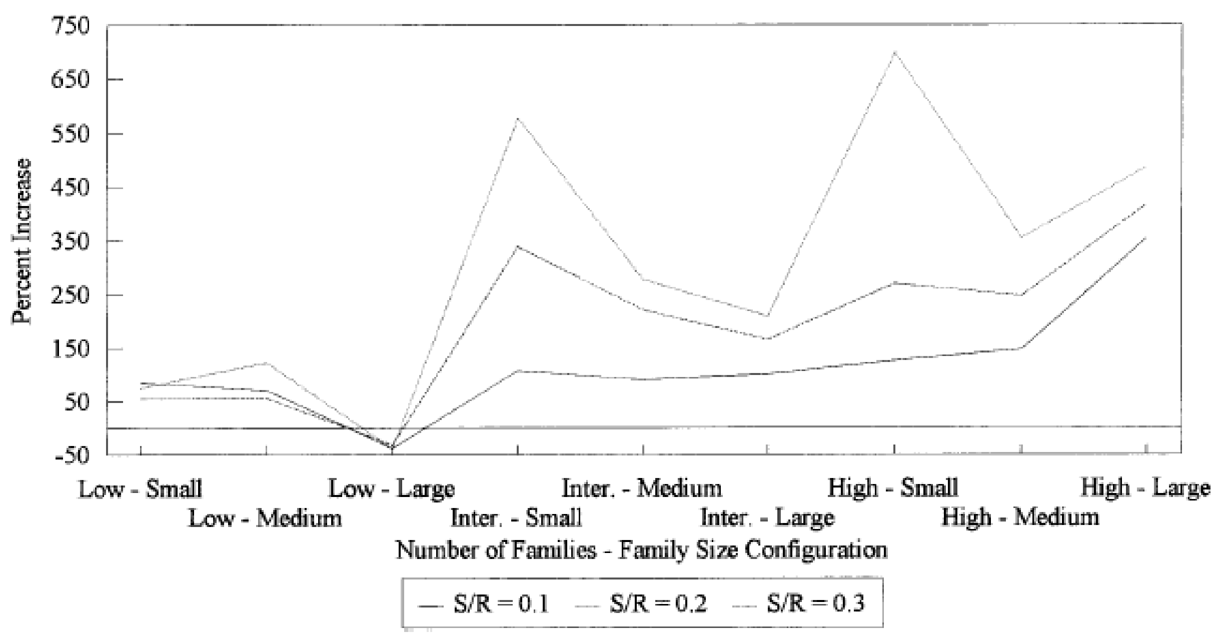


Figure 6. Percentage increase in mean tardiness attributable to use of job shops.

number of families due to the physical re-organization this necessitates.

The relatively large impact of family size is somewhat surprising. One would expect some deterioration in performance as family size increases. The corresponding decrease in likelihood of successive jobs being for the same part creates the need for an additional setup. If the number of families remains constant, this setup should typically be a minor setup in virtual cellular configurations, and a major setup in the job shop. Modest deterioration in performance in virtual cellular configurations and more significant deterioration in the job shop would thus be anticipated. The latter proved to be true when family size was increased from eight to twelve, particularly when *NFAM* was also high and setup reduction was at a premium. However, the virtual cellular configurations are also subject to more significant performance deterioration when family size is increased from eight to twelve. This seems to suggest that smaller, more homogeneous families are preferable to larger families. This is consistent with the observations that increasing the number of families has a relatively small effect. Further evidence of this can be obtained by comparing the performance when the total number of parts being produced is comparable but both aspects of family configuration are different. For example, when *NFAM* and *FSIZE* are two and eight, respectively (a total of 16 parts), mean flow time is 216.72 minutes ($S / R = 0.1$). However, when *NFAM* and *FSIZE* are five and four, respectively (20 parts), mean flow time is 201.78 minutes. This observation repeats itself for other pairs of *NFAM* and *FSIZE* values yielding similar total numbers of parts, and for different setup time conditions and performance measures.

An additional observation is that virtual cellular con- figurations have a significant impact on variance reduction. As Table 5 shows, the advantages of virtual cellular configurations are greater for σ_{FT} than for mean flow time. This is not unexpected. By recognizing families and thus reducing major setup frequency, virtual cellular manufacturing assumes some of the responsibilities of the order release system, smoothing shop load and reducing delays associated with queues that are typically the cause of large variance.

7. Conclusions

Virtual cellular manufacturing offers small batch manufacturers several advantages over a range of commonly found environments. Foremost among these is the potential to utilize production resources more efficiently, thereby lowering flow times and improving the ability to meet due dates. Viewing cells as flexible, adaptive entities, allows a shop layout that is inherently attractive in a dynamic environment to be utilized without sacrificing production efficiency or alternatively increasing batch size. The use of virtual cellular manufacturing also simplifies the task of allocating parts to families by giving producers the flexibility to define families more independently and to change their composition over time as demand patterns change. This research demonstrates that not only does virtual cellular manufacturing improve upon traditional job shop production, but that it effectively overcomes the limitations of traditional cellular manufacturing that plague producers, particularly that of responsiveness to changes in part mix.

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