World Review of Business Research
Vol. 1. No. 4. September 2011. Pp. 97-108

Reducing Manufacturing Flow Times: Job Shop Simulation and Reconfiguration

Glenn A. Metts* and Charles H. Apigian**

Smaller production companies, such as job shops, are often incapable of committing significant human or capital resources for the improvement of manufacturing flow times. However, there is considerable demand in these organizations for solutions that offer improvements without the risk involved in expending these resources. This paper investigates the impact of scheduling rules and reorganization (group technology) of manufacturing flows on a job shop as a low-cost solution to flow time improvement. It is proposed that a substantial reduction in flow times may be possible through the implementation of these alternatives. To ascertain these results, actual data from a job shop was used to aid in developing a simulation of their shop layout. With an initial baseline model, possible solutions were simulated to attain optimal flow times. The results indicated that the incorporation of scheduling rules and group technology led to a reduction in job arrival and process variation, which led to a significant reduction in flow times.

Keywords: (Job shop, simulation, group technology, cellular layout)

1. Introduction

In the job shop environment, the need to improve manufacturing flow times has always been a critical factor to stay competitive. Simply adding human resources or capital equipment may improve flow times, but these alternatives can add tremendous fixed cost and risk to an organization. Most job shops cannot afford the investment needed to reduce their manufacturing flow time. Therefore, a more economical alternative would be of great value to smaller organizations.

There are several solutions a job shop could use to improve flow times. However, most include a significant initial investment of labor or capital. Two alternative ways of reducing manufacturing flow times are scheduling rules and layout reconfiguration. If scheduling rules are not currently used in a company, then the use of a few rules, such as shortest processing time or earliest due date, on a shop floor will reduce wait times and eventually overall flow times. However, simple scheduling rules alone may not improve shop performance (Barmin and Lisboa, 2010), but coupled with layout reconfiguration, such as group technology which reduces setup times and variance, a job shop may see improved flow time performance.

From prior literature we know that employing scheduling rules or group technology concepts that significant improvement in flow times can be achieved (Shahin and Janatyan, 2010). However, there are relatively few studies that are based on the case approach where a team works with a “live” job shop and attempts to make improvements based on the application of concepts that we in academia readily accept, but seldom test. In the few instances where tests have been conducted,

*Dr. Glenn A Metts, CPA, Department of Management and Marketing, University of the Virgin Islands, US Virgin Islands, Email: gmetts@uvi.edu

** Dr. Charles H Apigian, Jones College of Business, MiddleTennesseeStateUniversity, Murfreesboro, TennesseeUSA, Email: charles.apigian@mtsu.edu

evidence of improvement is scarce (Barman and Lisboa, 2010). In this study, we seek to improve the flow times in a “tool building” shop active in the automotive industry in the US. Because of pressure from foreign competition it is imperative that flow times and efficiencies are improved in order to remain competitive.

Flow time is the amount of time a job spends from the moment it is ready for processing until its completion, and includes any waiting time prior to processing (Silver et al. 1998). In order to decrease manufacturing flow times significantly, job shops should consider reconfiguring their system to better accommodate the workflow. Many job shops still have a functional layout to their shop floor that fosters a first-come first-serve (FCFS) mentality that can easily create bottlenecks within their system. The ability to improve flow times through an optimized layout may enable an organization to become more efficient without additional capital or labor.

This study looks at alternative ways to reduce manufacturing flow times in a job shop environment that will not add a tremendous amount of cost or risk to an organization. Multiple trials were conducted through the use of common software packages including Simul8 (Simul8 Corp., Herndon, VA.), Microsoft Excel 2007 (Microsoft Corp., Redmond, WA.), and SPSS 12.0 (SPSS, Inc., Chicago, IL.), to simulate the floor of an actual job shop. The use of scheduling rules at specific bottlenecks and the reconfiguration of machines into groups based on product similarity were tested to identify opportunities for improvement in manufacturing flow times.

To identify the proper techniques for reduced flow, an examination of existing literature on job shop reconfiguration and scheduling rules was first conducted. Next, six months of data was gathered from the job shop and a baseline model was built using Simul8 (with Visual Logic) to simulate their shop floor. The baseline model was then modified to simulate potential improvements from the application of scheduling rules and group technology. Inefficiencies and bottlenecks within the system were identified. Based on the simulation results, changes were made using scheduling rules and a reconfiguration of the layout. Finally, alternative models were tested and measured against the baseline model to identify significant reductions in flow times.

2. Literature Review

A job shop environment is unique in its ability to manufacture. Normally, it does not follow an assembly line approach to production; instead it follows a more functional layout where jobs are processed as they reach the next operation in the process. In many cases, a job shop’s only advantage over competitors is its ability to process work more efficiently. This ability to improve flow times is critical to their success. Therefore, the issue of flow times is of high interest to a job shop.

2.1 Scheduling Rules

There are several types of scheduling rules that have been used to improve flow times and meet delivery dates. Many of the most basic rules used in the literature include First-Come First-Served (FCFS) (Pitchuka et al. 2006), Earliest Due Date (EDD) (Jensen et al. 1996), Shortest Processing Time (SPT) (Wang and Tang, 2011), and Critical Ratio (CR) (Silver et al. 1998).

The most basic deterministic schedule rule is FCFS. This is considered the simplest scheduling rule to incorporate. It requires the scheduling of jobs based on the time they enter a bin ready for processing. Although many job shops use this as part of their scheduling, it is in many cases the least optimal (Litchfield and Narasimhan, 2000). EDD scheduling rule puts a priority on the job that has the earliest delivery date. It looks to minimize lateness and tardiness (Silver et al. 1998). SPT is the sequencing of jobs in increasing order of their sum of the processing times on all machines. This scheduling rule is considered the optimal choice for the minimization of flow times (Kaminski and Simchi-Levi, 2001). CR incorporates both SPT and EDD to create a balance between the minimization of lateness and the minimization of flow times. For this study, SPT is the logical choice to use, since flow times are the main concern.

2.2 Job Shop Layout

The techniques used to reduce flow times in a job shop environment also include a reconfiguration of the shop floor. Reconfiguration enables a shop to minimize move times and simplify processes. However, in a small business, move times are normally not an issue. More substantial changes are needed in a small job shop environment in order to improve flow times. One of the ways of making a considerable layout change is to incorporate group technology and cellular manufacturing (Wemmerlov and Hyer, 1989).

Cellular manufacturing (CM) is a form of group technology, which looks to achieve efficiency by exploiting similarities inherent in parts (Shahin and Janatyan, 2010). Parts with similar process requirements are put into part families. A cell is then created that includes the labor and capital to produce a family (Shaeffer and Meredith, 1998). A look at the existing literature shows that job shop performance and cellular manufacturing has been combined with mixed results (Selim et al. 1998; Nomden and Zee, 2008). Early studies indicated that functional layout design outperformed cellular layouts (Flynn, 1987; Reisman et al., 1997; Suresh and Meredith, 1994), with the loss of pooling synergies hard to overcome for a cellular layout (Wemmerlov and Hyer, 1989).

There are five advantages of cellular layouts for job shops (Wemmerloz and Vakharia, 1991), which include lot sizing, a reduction in setup times, a lessening in the variability of process times, a reduction in the variability of job arrivals, and a decline in processing times through productivity improvements (Wemmerlov and Hyer, 1989). The ability to produce parts in smaller lots (lot sizing) may be of benefit to a job shop, but it has not been found to reduce manufacturing flow times. Most of the research in CM refers to the reduction of setup times as the main reason for incorporating the technique (Morris and Tersine, 1990). However, these studies looked at CM in a single machine environment and did not take into consideration an entire shop floor with multiple process, parts, and machines (Wemmerlov, 1992; Barman and Lisboa, 2010). For job shops that do not produce more than one customized piece of tooling at a time, setup times are not a consideration as they are always required for the next part to be processed.

Although most of the CM and GT literature identifies setup times as its main benefit, any reduction in processing times would counteract any losses in efficiencies due to this technique (Wemmerlov and Hyer, 1989). The grouping parts or specific types of jobs into families enables a shop to hone its craft in specific areas and improve productivity (Wemmerlov and Hyer, 1989). It also will influence material handling, job satisfaction, quality, required space, and finished product and labor costs ((Shahin and Janatyan, 2010). This advantage would be difficult to measure due to its indirect relationship to CM. One area that has not been tested, but has been identified as a plausible benefit is the reduction of variability in processing times and job arrivals (Reisman, Kumar, Motwani, and Cheng, 1997). Reduction in variability is directly related to the grouping of families of parts and processes. Not only may it reduce flow times, but it may enable an organization to more accurately predict the time that it will take to process an order.

An aim of this study is to show that reconfiguration of processes with cellular manufacturing and group technology will lead to reduced manufacturing flow times. Since setup times have been covered extensively in the literature, it is not considered in this study. This allows this study to isolate the effects of reconfiguration, scheduling rules, and variance reduction. Therefore, reconfiguration and scheduling rules to reduce processing times are the only changes in the system.

3. Experimental Design

In order to provide evidence that the combination of scheduling rules and group technology will lead to reduced manufacturing flow times, this study sought to identify a job shop that would benefit from these techniques. A job shop was found that utilized only basic FCFS scheduling rules and did not incorporate any grouping of parts or processes. The company used in this study manufactures customized tooling and gaging for the automotive industry. They do not have a standard set of products and most of their gages or tooling is made from in-house custom design or customer supplied blueprints. They do not make multiples of any of their jobs; each job is built one at a time. This alleviates the need to reduce setup times. Since each process is specific for that job, each setup is unique and necessary regardless of grouping. They also employ only one shift, which was eight hours in duration at the time of the study.

There are four main types of jobs that are processed through their system, with each relating to gaging. A gage is a device that checks the dimensions of a specific part on the production line to ensure it meets specifications. For example, a crankshaft for an engine has multiple diameters and lengths that must be within certain dimensions for it to pass inspection. A gage from this company could be used to measure a diameter to ensure that it is within their tolerance. Therefore, they would build an entire gage assembly, which would include a number of small details that are assembled into one fixture. They could also receive a job to repair a gage assembly, which means that a gage that is worn or broken may be sent to them to be refurbished. The final two types of jobs are the build or repair of a specific detail of a gage assembly. In many instances, a customer may order a specific detail that is part of an assembly to be built new or repaired. This happens in cases where specific details are known to wear or break and can be replaced by the customer without the assistance of the gage company. To draw an analogy, a car may not be able to start and the owner knows it is a problem with the ignition starter. Instead of sending the car in for service (similar to repair of a gage assembly), the owner buys a replacement for the one that does not work (similar to build new detail), and replaces the starter by themselves. (See Table 1 for a summary of the product types).

Table 1: Summary of Product Types

Product Type	Description	Typical Processes
Build gage assembly	The complete build and fabrication of a gage, including all of its details. This is the most time consuming type of job in the shop.	This would be built from raw steel, therefore a lot of rough machining and grinding would be necessary. Also, after all details are made, assembly, inspection, and packaging would take a considerable amount of time.
Repair gage assembly	The receipt of a worn-out or broken gage and restoration to new condition.	Since most details only need to repaired, this type of job includes more grinding than rough machining. Most details for the assembly can be chromed and reground to size.
Build detail only	The complete build of one detail that may be used in a gage assembly.	This is similar to the build gage assembly processes, but on a much smaller scale. Also, no assembly is needed.
Repair detail only	The repair of a worn-out or broken detail. It the detail is not salvageable, it may have to be replaced altogether.	Includes grinding, chroming, and regrinding to size, if the piece is salvageable.

To simulate the process of producing the four different types of gaging, a common simulation package, Simul8 2000, was used to create a baseline model of the shop floor. Since the organization did not have the resources to use an expensive or custom simulation package, we felt it was necessary to show that a common and inexpensive simulation package would suffice. Six months of data was compiled showing man-hours for each specific job (176 different jobs) that went through their system.

The process was divided into five major operational steps: rough machine, outsourced treatments, rough grind, finish grind, and assemble, inspect, and package. Table 2 shows the specific machines or treatments within each process, with the work of the organization classified into four distinct product types.

Table2: Descriptive Statistics for each Product Type and Process

Process	Machine	Product Type	Mean Time	Distribution
Inter-arrival Times				
		Build detail only	13.77	Exponential
		Build assembly	52.91	Exponential
		Repair detail only	27.14	Exponential
		Repair assembly	68.23	Exponential
Rough machine				
	Lathe	Build detail only	2.4763	Exponential
		Build assembly	15.6125	Exponential
		Repair detail only	.4583	Exponential
		Repair assembly	1.5526	Exponential
	Mill	Build detail only	2.7842	Exponential
		Build assembly	60.3125	Exponential
		Repair detail only	1.1488	Exponential
		Repair assembly	1.8816	Exponential
Outsourced Treatments				
	Heat Treat	All types	8 or 16	Fixed
	Black Oxide	All types	8	Fixed
	Freeze	All types	8	Fixed
	Chrome	All types	8	Fixed
Rough Grind				
	Various	Build detail only	2.5632	Exponential
		Build assembly	21.3375	Exponential
		Repair detail only	2.0119	Exponential
		Repair assembly	5.8421	Exponential
Final Grind				
	Various	Build detail only	4.3500	Exponential
		Build assembly	24.0375	Exponential
		Repair detail only	3.9345	Exponential
		Repair assembly	8.3026	Exponential
Assemble, inspect, and package				
	Assemble, Inspect, and Package	Build detail only	.2000	Exponential
		Build assembly	8.05000	Exponential
		Repair detail only	0.500	Exponential
		Repair assembly	1.6316	Exponential

The mean times for each process and machining operations were calculated and categorized by product type using Microsoft Excel 2007. The distribution types were determined based on visual inspection and the analysis of Q-Q plots to test fit. As shown in Table 2, the distributions of arrivals and of the machining centers were exponential in nature. Distributions for outsourced treatments were based on delivery schedules of the vendor. All outsourced operations were picked up or delivered at approximately the same time everyday, which gave a fixed turnover in hours, except heat treat, which could be either 1 or 2 days. Therefore, a mean of eight hours represents one full day outside of the facility, and distributions of the outsourced treatments are fixed.

3.1 Baseline Model

The initial model was designed to simulate typical operations of the company used for this study. The use of Simul8 does have its limitations, therefore Visual Logic was also used to specify routings and identify labels for each type of product. Since the performance measure is manufacturing flow time, the simulation was developed to imitate the company's systems based on hours for each job within the system. The mean manufacturing flow times (in hours) for each job were calculated. Results from this initial baseline simulation indicated that the performance was not significantly different than the actual data (See Table 3). Also included in the analysis was a test to check for significant differences between variances in the baseline model and actual data (Table 3); no differences were found. This was an important step to include, since this paper looks at variance reduction as a way to reduce flow times. The baseline simulation model was presented to the management of the company, to ensure that it logically made sense to them prior to use. After review of the model, the company agreed that it was a fair representation of their system. Therefore, it was determined that the model approximated the actual shop floor systems.

Table 3: T-Test for testing the differences between the simulated model and the actual model (assuming that the variances are different)

	Actual	*Baseline Model*
Mean	161.29	178.99
Variance	4456.73	5950.90
Number of Jobs Used	176	
Number of Simulated Trials		20
t Stat for means	-0.9113	
P value	0.3621^{ns}	
F Stat for variances	1.3353	
P value	0.2027^{ns}	

The initial attempt to reduce manufacturing flow times was focused on bottlenecks in the system. A simulation was run for a six-month period (1040 hours), with a total of 20 trials. After reviewing the average queue times and processing times, it was determined that the lathe-machining center was a bottleneck for the system with an average queue time of 200.48 hours. When management of the company was asked about the bottleneck, they agreed with our analysis and pointed out that in many instances, they outsourced their lathe work, which was not cost effective. Management also did not have enough resources, equipment, or workers to accommodate the bottleneck and did not want to invest additional capital in their system. The scheduling rule of shortest processing time was proposed for the lathe to see if this would reduce flow times.

3.2 SPT Model

Our second model was the same as our baseline model, except that shortest processing time (SPT) was used as a scheduling rule for the lathe. To develop this model, the initial Simul8 model was used and the scheduling rule was incorporated by using label-based distributions and Visual Logic to set the priority in the queue. The simulation was then conducted using 20 correlated trials of 1040 hours resulting in the reduction of mean flow time from 178.99 hours to 107.46 hours *(p-value = 0.000)*. Additionally, the average queue time at the lathe was reduced from 200.48 hours to 70.92 hours. Although the manufacturing flow time was reduced considerably, to fully optimize the shop floor layout, an alternative model using group technology was tested.

3.3 Group Technology (GT) Model

In discussions with the management of the company, they emphasized that the rough machining operations were usually the areas that had the highest inefficiencies. The lathe was a bottleneck for the process flow, but the milling station was also mentioned as a problem if large assembly jobs were in the system. The average processing time of the mill-machining center for the build of an assembly was 60.3125 hours, which was considerably higher than the other three product types (See Table 2). It was recommended to the company that product types be grouped into families and machines be dedicated for the different processes with the intent of a material reduction in the variation of each machining center.

The formulation of product families was based on the product types and the available resources of the lathe and mill. Since only two lathes were available, it was decided that the smaller product types and the build and repair details would be grouped into one family and serviced with the first lathe. The second lathe was dedicated to the other two product types; the build and repair assemblies. This allowed smaller jobs to get through the system without being held up by larger jobs. Additionally, since the scheduling rule SPT was already being used for the lathe area, larger jobs will be able to move through the system without being passed up for shorter processing times.

There were three available mills in the company, which allowed three groupings of product types for this stage. Since the build of assemblies required the largest processing time, a single mill was dedicated to that type of product. The second mill was dedicated to the repair of assemblies, since this was the second largest processing time. Therefore, the build and repair of details only were dedicated to the third mill, which allowed jobs with smaller processing times through the system without getting stopped due to the milling of a large assembly. Since FCFS was being utilized as the scheduling rule for the milling process, a constant flow of jobs could be streaming through the system without being stopped by large or a high quantity of small jobs.

After reviewing the resources available for the rough grind and finish grind, it was decided that after the milling process, the shop would dedicate product types to specific grinding machines within each process. This would continue the flow of the work throughout the system, based on the GT concept (See Table 4). The outsourced treatments, which have unlimited capacity, and the assembly, inspect, and package process were maintained as in previous simulation models. Also, no additional capital or human resources were added to accommodate the changes.

To facilitate these changes in Simul8, “dummy” variables and Visual Logic were used throughout the simulation model. “Dummy” variables acted as routers and were used after jobs were specified as one of the four types of products. Although this was a complicated task and problems were identified within the Simul8 software, the results of the simulation were significant.

Table 4: Grouping of Product Types for Different Processes

Process	Product Types			
	Product Type 1 Build Details Only	Product Type 2 Build Assemblies	Product Type 3 Repair Details Only	Product Type 4 Repair Assemblies
Lathe	Lathe #1	Lathe #2	Lathe #1	Lathe #2
Mill	Mill #1	Mill #2	Mill #1	Mill #3
Heat Treat	Infinite	Infinite	Infinite	Infinite
Black Oxide	Infinite	Infinite	Infinite	Infinite
Freeze	Infinite	Infinite	Infinite	Infinite
Chrome	Infinite	Infinite	Infinite	Infinite
Rough Grind	RG #1	RG #2, 3, and 4	RG #5	RG #6
Final Grind	FG #1	FG #2, 3, and 4	FG #5	FG #6
Assembly, Inspect, and Package	Any Resource	Any Resource	Any Resource	Any Resource

Note:
Infinite is defined as an unlimited capacity, which is due to the outsourcing of these processes

4. Results

After the shop was reconfigured to the GT model specifications, twenty trials of 1040 hours were run per the process flow indicated in Table 4. The manufacturing flow time was reduced to 66.80 hours (See Table 5). This final result, compared to the results of the initial model (178.99 hours) and the SPT model (107.46 hours), showed the dramatic improvement within the system achieved without investment in equipment or human resources while utilizing common software. Paired t-tests were performed to test for differences between the three simulated models; all differences were found to be significant (See Table 5). Since the randomly generated data for the simulation were identical for each model, paired t-tests were used. T-tests with unequal variances were conducted to test the differences between the actual results and the three models, since simulation and actual data realistically do not vary the same.

Although the mean flow time from the actual data was not significantly different than the baseline model (as established in the initial testing of the simulation model), it was significantly different than the SPT model *(p-value = 0.0375*) and the GT model *(p-value = 0.0004)*. While these results indicate a statistically significant effect, the actual decline in mean manufacturing flow times was considerable (from 161.29 hours to 66.80 hours.) The baseline model was also significantly different than the SPT model *(p-value = 0.000)* and the GT model *(p-value = 0.000)*, which reaffirms the replication of the actual shop floor through the baseline model. It should also be noted that the addition of group technology reduced flow times significantly compared to the SPT model *(p-value = 0.000)*.

Table 5: T-Tests testing for differences between configurations

Models	Actual Data	Baseline Model	SPT Model	GT Model
Actual Data[a]		*t-value = -0.9113* *p-value = 0.3621*	*t-value = 2.1267* *p-value = 0.0375*	*t-value = 3.8114* *p-value = 0.0004*
Baseline Model[b]			*t-value = 5.18* *p-value = 0.0000*	*t-value = 6.493* *p-value = 0.0000*
SPT Model[b]				*t-value = 7.160* *p-value = 0.0000*
Mean	161.29	178.99	107.46	66.80
Variance	4456.73	5950.90	566.50	43.19
No. of Trials	176[c]	20	20	20

Note:
[a] Tests for differences were t-tests assuming unequal variances
[b] Tests for differences were Paired t-tests
[c] Represents the number of jobs used during data collection

5. Discussion

The only changes to the system to improve manufacturing flow times were the incorporation of the SPT scheduling rule at the lathe operation and the grouping of processes to dedicated machines or group technology. The final simulation model, based on group technology, provided the best model for the reduction of flow times. Of the five advantages of cellular layouts or group technology, the only plausible driver of reduced flow times in this study was variance reduction. Setup times were not a consideration, since the organization used for the study made customized tooling that had setup times for each piece of a job for every operation. Lot sizing is an advantage, but not a driver of a reduction in flow times. Although productivity may be improved due to a higher degree of specialization in processes, it was not a factor that was simulated in this study. Variance reduction in processing and job arrivals was the determining factor for the substantial improvement in throughput.

Job arrival variability was affected due the placement of jobs. Since all large gage assemblies were placed on the same machine (Lathe #2) and the smaller detail jobs were placed on the same machine (Lathe #1), the inter-arrival variability was reduced. The grouping of these processes allowed smaller detail-only jobs to get into the system without being queued behind a large assembly. Compared to the baseline model queue time of 200.48 hours, the queuing times under the GT model for Lathe #1 and Lathe #2 were only 1.70 hours *(t-stat 6.58, p = 0.000)* and 25.68 hours *(t-stat 5.68, p = 0.000)* respectively. The variability of the queuing times was also drastically reduced, as evident by the change in variances from 1040.02 (baseline model) to 0.05 (Lathe #1 for GT model) and 18.58 (Lathe #2 for GT model). This reduction aided in reducing the manufacturing flow times.

Additional variance reduction was achieved in the processes. By grouping the processes based on the type of job, the variance for each machine was lessened. As the average time in the system fell from 178.99 (baseline model mean) to 66.80 (GT model mean), so did the variances: 5950.90 (baseline model variance), 566.50 (SPT model variance), and 43.19 (GT model variance). To establish the significance of these changes, the variances were statistically tested. Using a two-sample F-test for variance, it was determined that the variances between each of the models were significantly different (*p-values < 0.000*). The variance and average time in the system for each run was then analyzed through regression to determine if a relationship between the reduction in variance and manufacturing flow times exists. According to the regression analysis, there is a significant relationship between variance and average time in the system with a coefficient of 0.0033 *(t stat = 14.33, p-value = 0.000*); further evidence of a link between variance and manufacturing flow times.

The practical implications of these findings are quite interesting. Smaller job shops should understand that additional investment in capital and labor is not always the answer to higher productivity. Prior to making a commitment to additional resources, a job shop should explore its options for shop floor reconfiguration. By grouping processes or parts into families, the reduction in job arrival variation and process variation will lead to reduced flow times.

6. Conclusion

This study was aimed at identifying alternative configurations of job shops without investing in additional capital or human resources, and by using commonly available software packages. After collecting six months of data (176 jobs), a simulation model was developed to approximate the actual shop environment. Based on the results from this initial model, two alternative models were developed. The final model that incorporated group technology and scheduling rules provided the best alternative in terms of average flow times and minimal variation. This study shows that flow times can be improved without investing in additional resources. The results are significant for job shops, especially smaller businesses that cannot afford to continually invest in new equipment or hire additional workers. The reconfiguration of a shop floor into a group technology environment can reduce manufacturing flow times, which will improve delivery times without additional investment. This assist job shops in remaining competitive in an environment that continues to demand shorter manufacturing flow times.

References

Barman, Samir and Joao Lisboa, 'Cost Performance of Simple Priority Rule Combinations', *Journal of Manufacturing Technology Management*, 21(5), 2010, 567-584.

Flynn, BB and RF Jacobs, 'A Simulation Comparison of Group Technology with Traditional Shop Manufacturing', *International Journal of Production Research*, 24(5), 1986, 1171-1192.

Flynn, BB, 'Repetitive Lots: The Use of Sequencing-Dependent Setup Time Scheduling Procedure in Group Technology and Traditional Shops', *Journal of Operations Management*, 7 1987, 203-216.

Flynn, BB and RF Jacobs, 'An Experimental Comparison of Cellular (Group Technology) with Process Layout' *Decision Sciences*, 18(4), 1987, 562-581.

Jensen, JB, Malhotra, MK and Philipoom, PR, 'Machine Dedication and Process Flexibility in a Group Technology Environment', *Journal of Operations Management*, 14(1), 1996, 19-39

Kaminsky, P and D Simchi-Levi, 'The Asymptotic Optimality of the SPT Rule for the Flow Shop Mean Completion Time Problem', *Operations Research*, 49(2), 2001, 293-304.

Litchfield, J and R Narasimhan, 'Improving Job Shop Performance through Process Queue Management under Transfer Balancing', *Production and Operations Management*, 9(4), 2000, 336-348.

Morris, JS and RJ Tersine, 'A Simulation Analysis of Factors Influencing the Attractiveness of Group Technology Cellular Layouts', *Management Science*, 36(12), 1990.

Nomden, G and D. Zee, 'Virtual Cellular Manufacturing: Configuring Routing Flexibility', *International Journal of Production Economics*, 112(1), 2008, 439–451.

Pitchuka, LN, GK Adil, and U. Ananthakumar, 'Effect of the Conversion of the Functional Layout to a Cellular Layout on the Queue Time Performance: Some New Insights', *International Journal of Advanced Manufacturing Technology*, 31(5/6), 2006, 594-601.

Reisman, A, A. Kumar, J. Motwani and CH Cheng, 'Cellular Manufacturing: A Statistical Review of the Literature (1965-1995)', *Operations Research*, 45(4), 1997, 508-520.

Selim, HM, RG Askin, and AJ Vakharia, 'Cell Formation in Group Technology: Review, Evaluation and Directions for Future Research', *Computers & Industrial Engineering*, 34(1), 1998, 3-20.

Shaeffer, SM and JR. Meredith, *Operations Management: A Process Approach with Spreadsheets*, 1998, John Wiley and Sons, New York.

Shahin, Arash and Nassibeh Janatyan, 'Group Technology (GT) and Lean Production: A Conceptual Model for Enhancing Productivity', *International Business Research*, 3(4), 2010, 105-118.

Shambu, G and NC. Suresh, 'Performance of Hybrid Cellular Manufacturing Systems: A Computer Simulation Investigation', *European Journal of Operational Research*, 120(2), 2000, 436-458.

Silver, EA, DF. Pyke and R. Peterson, *Inventory Management and Production Planning and Scheduling*, 3rd ed., 1998, John Wiley and Sons, New York.

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

Suresh, NC and JR. Meredith, 'Coping with the Loss of Pooling Synergy in Cellular Manufacturing Systems', *Management Science*, 40(4), 1994, 466-483.

Wang, X and L. Tang, 'Scheduling a Single Machine with Multiple Job Processing Ability to Minimize Makespan', *Journal of the Operational Research Society*, 62(8), 2011, 1555-1565

Wemmerlov, U and NL. Hyer, 'Cellular Manufacturing Practices', *Manufacturing Engineering*, 102(3), 1989, 79-82.

Wemmerlov, U and AJ. Vakharia, 'Job and Family Scheduling of a Flow-Line Manufacturing Cell: A Simulation Study', *IIE Transactions*, 23(4), 1991, 383-393.

Wemmerlov, U, 'Fundamental Insights into Part Family Scheduling: The Single', *Decision Sciences*, 23(3), 1992, 565-595.