

The threshold value of a quality index for formation of cellular manufacturing systems

H. SEIFODDINI† and M. DJASSEMI‡

The superiority of cellular manufacturing to job shop manufacturing has been questioned by a number of simulation studies. The initial structure of the machine-part matrix seems to play an important role in the failure of cellular manufacturing systems in these studies. In this paper a grouping measure called 'quality index—QI' will be used to evaluate the relationship between the quality of a machine-part matrix and the performance of the corresponding cellular manufacturing system. A simulation study will be conducted to demonstrate how the procedure can be used to determine the threshold value for QI beyond which the cellular manufacturing system outperforms the corresponding job shop manufacturing system.

1. Introduction

Manufacturing is undergoing one of its most profound changes since the introduction of mass production. Globalization has created a competitive environment in which only the most efficient corporations survive. As a response to this challenge manufacturers all over the world are using the most innovative manufacturing techniques available. One such technique is cellular manufacturing (CM) which overcomes the inefficiencies of traditional batch-type manufacturing through reduction in setup times, in-process inventories, and throughput times. In CM the benefits of economy of scale is achieved by grouping similar parts into part-families and processing them into dedicated machine cells (Burbidge 1975, Hyer 1984). Ideally a part-family is processed in a single machine cell for its entire operations. In practice, however, some parts (exceptional parts) have operations on machines (bottleneck machines) outside their parent cell (King 1980).

Data for formation of machine cells and part-families is organized in the machine-part (M-P) matrix which is a binary matrix with zero one entries. A 'one' entry in row i and column j of the matrix indicates that part j has an operation(s) on machine i while a zero entry indicates it does not. The machine cell formation algorithms convert the M-P matrix into a block diagonal form in which 'one' entries are concentrated in blocks along the diagonal of the matrix. Each block represent a machine-component group in the corresponding CM system (Seifoddini and Wolf 1986). The initial structure of a M-P matrix to a great extent determines the performance of the corresponding CM system.

As an attempt to evaluate the goodness of a M-P matrix, a number of grouping measures such as bond energy (McCormick, *et al.* 1972), grouping efficiency (Chandrasekharan and Rajagopalan 1989), grouping efficacy (Kumar and Chandrasekharan 1990) and grouping capability index (Hsu 1990) have been developed. Most

†Industrial and Manufacturing Engineering Department, University of Wisconsin, Milwaukee, USA.

‡Industrial Studies Department, University of Wisconsin, Platteville, USA.

of these measures are based on the relative number of 'one' entries inside and outside the diagonal blocks. Grouping efficiency tends to have a high value for complete block diagonal matrices in which all 'one' entries are inside the blocks.

While successful cases of CM are well documented (Wemmerlov and Hyer 1989) and (Hyer 1984), several simulation studies show that conversion from job shop to CM may result in inferior performance in some manufacturing systems. Contributing factors to performance deterioration include long queues in front of bottleneck machines, under utilization of non-bottleneck machines, and inflexibility of dedicated machine cells in dealing with changes in product mix (Ang and Willey 1984, Flynn and Jacobs 1986).

A study by authors indicates that there are some common characteristics in failed CM cases including dense M-P matrices. Therefore, the identification of such characteristics and establishment of their relations to the performance of the corresponding CM systems are two crucial steps toward more successful development of such systems.

In this paper a grouping measure called 'quality index-QI' is used to evaluate M-P matrices. Then simulation modelling will be employed to measure the performance of the corresponding CM system by estimating the average flow times, in-process inventories, and so on. Finally, a number of different M-P matrices are used to determine the relationship between different values of QI and the performance of the corresponding CM system. The purpose is to determine the threshold value of the QI beyond which CM system will outperform the corresponding job shop manufacturing system.

2. Definition of the problem

The benefits of CM has been questioned by a number of simulation studies including Christy and Udayan (1986), Flynn and Jacobs (1986), Sarper (1988), Garza (1990), Sassani (1990), and Shafer and Meredith (1990). These studies indicate that the formation of dedicated machine cells generally reduces the availability of machines for the processing of parts in the product mix. This leads to high inventory accumulation in front of bottleneck machines, low utilization of non-bottleneck machines and imbalanced workload distribution among machine cells. Cellular manufacturing is also less flexible in dealing with changes in the product mix.

Some of the above mentioned problems including the imbalanced workload distribution can be overcome by using alternative routing (Burbidge 1992), outsourcing (Burbidge 1975), machine duplication (Seifoddini, 1989) and the formation of hybrid machine cells (Seifoddini 1992). Some other problems, such as the inflexibility of dedicated machine cells in the case of changing product mix, merit careful analysis prior to any decision regarding the development of a CM system. Yet other problems, such as excessive intercellular moves and inefficient shopfloor operations, may be signs of ill-suited situations for conversion to cellular manufacturing. Therefore each manufacturing situation should be carefully evaluated before conversion to CM.

In a simulation study by Flynn and Jacobs (1986), the conversion from job shop manufacturing to CM led to longer queues, higher work-in-process inventories, and longer waiting lines. In this study the characteristics of the manufacturing system including its dense M-P matrix (Shafer and Meredith 1990) might have been the main reason for the poor performance of the corresponding CM system. Generally, the structure of the M-P matrix has a great impact on the performance of the corresponding CM system. Therefore, the evaluation of the block diagonal M-P matrix provides

useful information on its suitability for the development of a CM system. The three important components of such an evaluation include a grouping measure, performance measures, and a simulation model.

Among the existing grouping measures, quality index (QI) is the most effective one (Seifoddini and Djassemi 1994). QI is the measure of independence of machine-component groups. Since independent machine cells are ideal for the formation of CM systems, a high value of QI is expected to lead to a high performance level in the corresponding CM system.

QI can be defined as,

$$QI = 1 - \frac{ICW}{PW}$$

where,

ICW = Total intercellular workload

PW = Total plant workload

ICW, on the other hand, can be defined as

$$ICW = \sum_{C=1}^C \sum_{M=1}^M \left[Y_{mc} \left(\sum_{P=1}^P (1 - Z_{pc}) X_{mp} V_p T_{mp} \right) \right]$$

where,

$$Y_{mc} = \begin{cases} 1, & \text{if machine } m \text{ is assigned to cell } c \\ 0, & \text{otherwise} \end{cases}$$

$$Z_{pc} = \begin{cases} 1, & \text{if part } p \text{ is assigned to cell } c \\ 0, & \text{otherwise} \end{cases}$$

$$X_{mp} = \begin{cases} 1, & \text{if part } p \text{ has operation on machine } m \\ 0, & \text{otherwise} \end{cases}$$

V_p = volume of part p

T_{mp} = processing time of part p on machine m

M = total number of machines

P = total number of parts

C = total number of cells

PW can be defined as,

$$PW = \sum_{m=1}^M \sum_{p=1}^P X_{mp} \cdot V_p \cdot T_{mp}$$

X_{mp} , V_p and T_{mp} as defined before.

For performance evaluation, measures such as mean flow time, mean work-in-process inventories, mean set-up time, mean number of intercellular moves, and mean operator productivity are widely used in the literature and will be employed here (Djassemi 1994).

In order to compare the performance of a manufacturing system under job shop

and CM configuration, a simulation model is used. In the simulation analysis, the performance of the manufacturing systems with different M-P matrices will be evaluated by using one of the above mentioned performance measures. Then the relationship between values of QI and the performance of the corresponding manufacturing system will be determined using statistical analysis. Finally, threshold value of QI beyond which the CM system outperforms its corresponding job shop manufacturing system is determined.

3. Comparison of job shop and cellular manufacturing

The comparison of manufacturing systems under job shop and CM configurations is done in three phases. In the first phase the M-P matrix is converted into a block diagonal form which is used to develop a CM system. The value of QI for the block diagonal form is also calculated at this phase. In the second phase, a simulation model of both job shop and CM system is constructed. This simulation model is used to estimate different performance measures for the two systems based on a number of different M-P matrices and their corresponding QI values. Finally, statistical analysis is used to test the significance of the differences between the performances of the two systems at different QI levels.

The algorithmic form of the procedure can be summarized as follows:

- (1) Convert the M-P matrix into a block diagonal form using one of the existing machine-component grouping algorithms such as ROC (King 1980) or SCM (Seifoddini and Wolf 1986).
- (2) Calculate the value of QI for the block diagonal form.
- (3) Use simulation to estimate the performance measures for both job shop and CM systems under a specific manufacturing situation.
- (4) Determine the statistical significance of the difference between the performances of the two systems.
- (5) Repeat steps 1 to 4 for a set of different M-P matrices and QI's. The value of QI can be changed,
 - (a) by redistribution of entries of the M-P matrix or
 - (b) by changing the density of the M-P matrix.
- (6) Determine the value of QI beyond which CM system outperforms its corresponding job shop manufacturing system.

Since a number of different performance measures have been employed in this study, it is expected that a range of QI values is determined as a threshold value for converting a job shop system to a cellular manufacturing system.

The procedure presented here is based on the following assumptions.

- (1) An efficient machine-component grouping algorithm is used to form machine cells for CM.
- (2) Raw materials are ready at the beginning of the shift.
- (3) Machine breakdowns are not considered (this can be a serious problem if the effects of machine breakdowns is significantly different in CM and job shop).
- (4) There is one operator for every two machines and job rotation occurs in machine cells.

This is a comparative study and hence it does not seem that these assumptions impose any serious limitation on the viability of results. Assumption 4, however, requires more exploration and can be the subject of a new study.

Since simulation is a major part of this procedure a brief discussion of important features of the simulation model will be presented in the following section.

3.1. *Simulation modelling*

SIMAN/CINEMA IV simulation language is used for model translation (Pegden *et al.* 1990). SIMAN provides a flexible modelling environment for manufacturing systems including built in features for modelling of work stations, transportations, waiting lines, and so on. CINEMA animation is also helpful, especially for model verification (Djassemi 1994).

Continuity and degeneracy tests (removing some machines and checking for performance deterioration) were conducted for model validation. Common random numbers were used for minimizing variations. The replication/deletion graphical method (Law and Kelton 1991) was used to minimize the effects of the transient period and the results for 100 days of simulation (50 000 time units) were discarded. Finally, batching method was used for parameter estimation (Law and Kelton 1991). Data for the steady state period were divided into 20 batches of size 13 days.

3.2. *Input data*

The main input to the simulation model include;

- (1) A M-P matrix which provides the information for the development of job shop and CM systems.
- (2) Routing and operational data including processing times and base setup times.
- (3) Product mix and arrival patterns.

M-P matrices for two manufacturing situations used in this paper are given in Figs 1 and 7. Additional M-P matrices for different QI values are given in appendix A of Djassemi (1994). The interarrival times for parts in the M-P matrices in Figures 1 and 7 are exponentially distributed with mean interarrival time of 10 minutes and 60 minutes, respectively. Data on the processing times of parts and their routings are given in appendix A of Djassemi (1994). In addition, it is assumed that the general time coefficient (GTC) for different sequencing possibilities is as follows:

- (1) For two identical parts loaded sequentially, $GTC = 0.1$,
- (2) For two parts from the same part-family loaded sequentially, $GTC = 0.5$,
- (3) For two parts from different part-families loaded sequentially, $GTC = 1$.

GTC is multiplied by the base setup time to generate setup times for different sequencing scenarios.

3.3. *Statistical analysis*

The difference between the mean performances of the two systems is used as the basis for their comparison. To determine the statistical significance of the difference, the paired-*t* test is employed. The following are provided.

- The difference between mean performance measures,
- Paired-*t* confidence interval for the mean differences,
- Test of hypothesis concerning the two means.

The following hypothesis is tested:

H₀: No difference exists between the performances of a job shop manufacturing

PARTS

		15	8	5	9	6	3	11	14	1	4	13	10	7	2	12	
M A C H I N E S	16	1		1	1	1											
	6	1			1	1	1									1	
	17	1	1	1								1					
	27	1	1	1													
	8	1	1		1												
	13	1		1	1							1					
	23			1													
	35	1			1												
	29	1		1													
	30				1												
	2					1		1									1
	20					1		1									
	7									1							
	15						1	1	1	1							
	11					1	1			1							
	28						1	1									
	36						1										
	18					1				1							
	21										1	1					
	32										1	1					
	3									1	1	1					
	9										1		1				
	34											1	1				
	4											1	1				
	24												1	1			
	5													1			
	19													1	1	1	
	25									1	1	1					1
	10											1				1	1
	22													1			1
12										1			1				
14	1													1	1		
33														1		1	
31														1	1	1	
26															1		

Figure 1. Machine-part matrix (QI = 0.78).

system and the corresponding cellular manufacturing system at a specific QI value.

The rejection of H_0 implies that one of the two systems is superior for the given QI values. To deal with the individual performance measures of a job-shop manufacturing system and the corresponding CM system, the above hypothesis should be modified as follows:

H_{01} : There is no difference between the mean flow times of the two systems.

H_{02} : There is no difference between the mean work-in-process (WIP) inventories of the two systems.

H_{03} : There is no difference between the mean setup times of the two systems.

H_{04} : There is no difference between the mean number of intercellular (inter-departmental) moves in the two systems.

H_{05} : There is no difference between the mean operator productivity in the two systems.

Rejection of any of these hypothesis is an indication of the superiority of one of the two systems with respect to the corresponding performance measure.

4. Analysis of results

In this section simulation results and the results of test of hypothesis for a number of different QI values are summarized. A brief discussion about each value of QI is provided.

The data on the product mix, machining requirements of parts, and machines are organized in the M-P matrix in Fig. 1. Other production data such as routings, the distribution of interarrival times, batch sizes of orders, base setup times, and modified versions of M-P matrix for different values of QI are in Djassemi (1994).

The QI value for the initial M-P matrix (Fig. 1) is 0.78. A QI value of 0.86 can be obtained by a 10% reduction in the density of the matrix. Another 10% reduction in the density of the matrix generates a QI value of 0.91. If all exceptional parts are eliminated from the matrix, a QI value of 1 is achieved. On the other hand, a 20% increase in the density of the matrix generates a QI value of 0.68.

The simulation results for the M-P matrix with the QI of 0.68 is given in Table 1. The results for the test of hypothesis (at $\alpha = 0.05$) are summarized in Table 2. At this QI level, the mean flow time and WIP are significantly higher in CM system. As expected the mean setup time and number of part movements are lower in the CM system. This leads to higher operator productivity for the CM system.

Shop type	Flow time (hours)	WIP (parts)	Setup time (%)	Number of intercell moves	Operator
Job shop	128*	3.02	19.9	21.13	3.17
	125–129**	2.98–3.12	19.5–20.2	20.2–21.18	3.15–3.20
CM shop	154	4.71	5.4	6.05	3.4
	152–157	4.53–4.84	5.3–5.52	5.95–6.13	3.32–3.51

*Mean **95% Confidence interval

Table 1. Simulation results for QI = 0.68.

Performance measure	Mean differences of two models and 95% C.I.	Test of hypothesis
Mean flow time	26 ± 2.4	Reject H_{0B1}
Mean WIP	1.67 ± 0.86	Reject H_{0B2}
Mean setup time	0.145 ± 0.006	Reject H_{0B3}
Mean # of intercell moves	15 ± 0.92	Reject H_{0B4}
Operator productivity	0.22 ± 0.11	Reject H_{0B5}

Table 2. Results of test of hypothesis for QI = 0.68.

Shop type	Flow time (hours)	WIP (parts)	Setup time (%)	Number of intercell moves	Operator
Job shop	105*	2.68	20	19.86	3.07
	101–108**	2.45–2.79	19.5–2.79	18.8–20.3	7.98–3.12
CM shop	112	3.52	5.1	3.17	3.48
	109–116	3.45–3.62	5.0–5.16	3.14–3.20	3.35–3.58

*Mean **95% Confidence interval

Table 3. Simulation results for $QI = 0.78$.

Performance measures	Mean differences of two models and 95% C.I.	Test of hypothesis
Mean flow time	7.0 ± 4.2	Reject H_{0B1}
Mean WIP	0.80 ± 0.09	Reject H_{0B2}
Mean setup time	0.145 ± 0.03	Reject H_{0B3}
Mean # of intercell moves	16.5 ± 1.14	Reject H_{0B4}
Operator productivity	0.40 ± 0.02	Reject H_{0B5}

Table 4. Results of test of hypothesis for $QI = 0.78$.

Shop type	Flow time (hours)	WIP (parts)	Setup time (%)	Number of intercell moves	Operator
Job shop	97.16*	3.04	20	19.79	3.51
	96.1–98.2**	2.99–3.14	19.2–20.3	19.2–20.01	3.46–3.62
CM shop	96.8	3.48	4.4	2.57	4.05
	96.2–97.3	3.41–3.53	4.1–4.6	2.45–2.66	3.97–4.13

*Mean **95% Confidence interval

Table 5. Simulation results for $QI = 0.86$.

Performance measure	Mean differences of two models and 95% C.I.	Test of hypothesis
Mean flow time	0.35 ± 0.52	Accept H_{0B1}
Mean WIP	0.45 ± 0.09	Reject H_{0B2}
Mean setup time	0.132 ± 0.08	Reject H_{0B3}
Mean # of intercell moves	17.2 ± 0.1	Reject H_{0B4}
Operator productivity	0.51 ± 0.016	Reject H_{0B5}

Table 6. Results of test of hypothesis for $QI = 0.86$.

When the original M-P matrix ($QI = 0.78$) is used, the simulation results and the summary of results for the test of hypothesis are given in Tables 3 and 4. At this QI level, the mean flow time and WIP are still higher in the CM system. It seems that a higher level of QI is needed to improve these two performance measures in the CM system.

If the density of the M-P matrix is reduced by 10% ($QI = 0.86$), the simulation results improve as shown in Table 5. At this QI level the difference between the two systems in terms of mean flow time is not statistically significant. Based on the WIP level, however, still the job shop system outperforms the CM system. The results for the test of hypothesis are presented in Table 6.

Shop type	Flow time (hours)	WIP (parts)	Setup time (%)	Number of intercell moves	Operator
Job shop	89.19*	2.74	20	18.9	3.2
	86.8-91.2**	2.69-2.82	19.8-20.2	18.2-19.01	3.09-3.22
CM shop	85.78	3.18	4.1	1.69	3.67
	84.1-86.2	3.11-3.21	4.01-4.14	1.56-1.72	3.58-3.71

*Mean **95% Confidence interval

Table 7. Simulations results for $QI = 0.91$.

Performance measure	Mean differences of two models and 95% C.I.	Test of hypothesis
Mean flow time	3.2 ± 0.9	Reject H_{0B1}
Mean WIP	0.24 ± 0.03	Reject H_{0B2}
Mean setup time	0.125 ± 0.003	Reject H_{0B3}
Mean # of intercell moves	17.2 ± 0.52	Reject H_{0B4}
Operator productivity	0.48 ± 0.02	Reject H_{0B5}

Table 8. Results of test of hypothesis for $QI = 0.91$.

Shop type	Flow time (hours)	WIP (parts)	Setup time (%)	Number of intercell moves	Operator
Job shop	82*	2.96	18.8	18.84	3.48
	81.2-82.6**	2.55-3.02	18.2-19.02	18.83-18.86	3.45-3.51
CM shop	66.3	2.13	3.9	0	3.94
	65.8-66.9	2.09-2.15	3.7-4.2		3.88-3.96

*Mean **95% Confidence interval

Table 9. Simulation results for $QI = 1$.

Performance measure	Mean differences in two models and 95% C.I.	Test of hypothesis
Mean flow time	15.6 ± 0.52	Reject H_{0B1}
Mean WIP	0.82 ± 0.08	Reject H_{0B2}
Mean setup time	0.145 ± 0.04	Reject H_{0B3}
Mean # of intercell moves	18.84 ± 0	Reject H_{0B4}
Operator productivity	0.46 ± 0.05	Reject H_{0B5}

Table 10. Results of test of hypothesis for $QI = 1$.

In the next trial the M-P matrix is further improved by another 10% reductions in its density ($QI = 0.91$). The simulation results for this QI are given in Table 7 and the results of test of hypothesis are presented in Table 8. At this QI level the performance of CM system further improves and it outperforms the job shop system in all performance measures except WIP.

Finally, when the M-P matrix is rearranged to achieve a QI value of 1, the simulation results indicate that CM system is outperforming the corresponding job shop system in all performance measures employed in this study. The simulation results and the results of test of hypothesis are given in Tables 9 and 10.

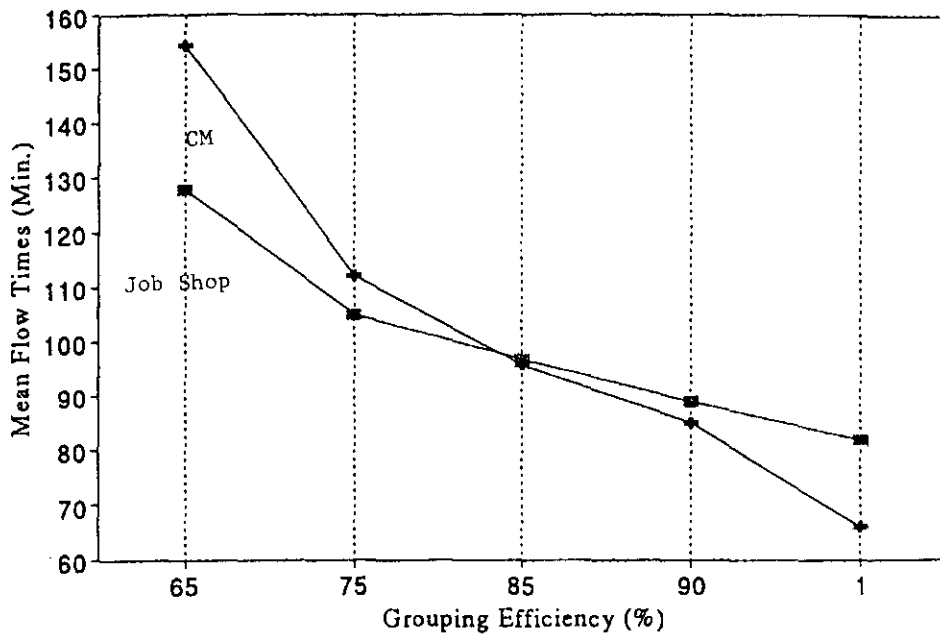


Figure 2. Comparison of mean flow times.

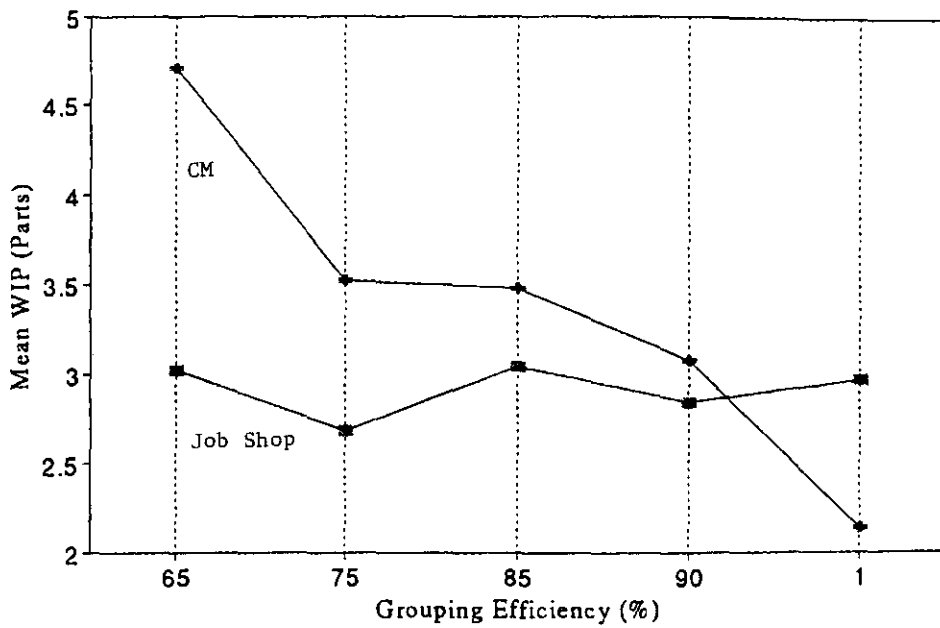


Figure 3. Comparison of WIP.

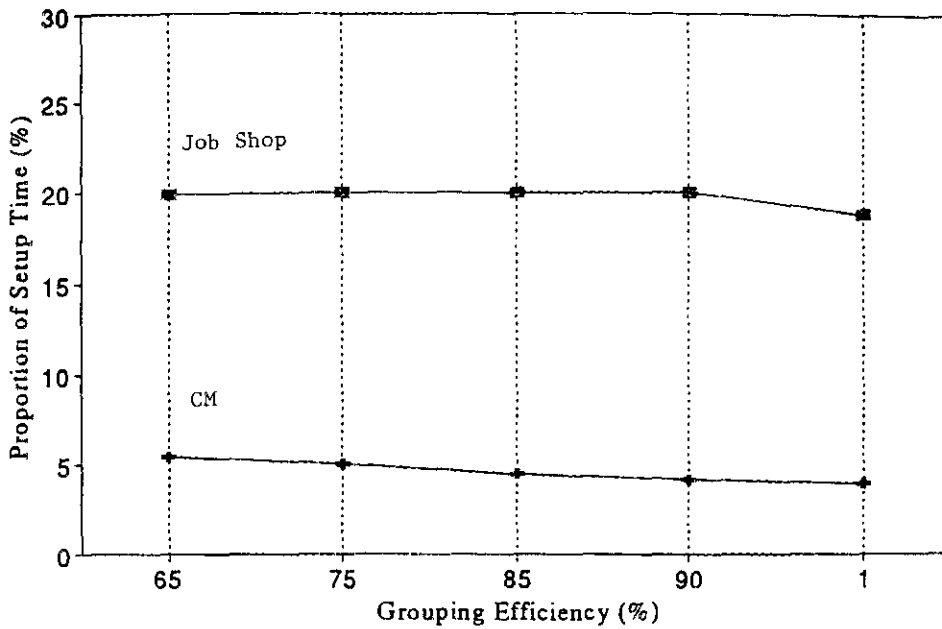


Figure 4. Comparison of proportion of setup time.

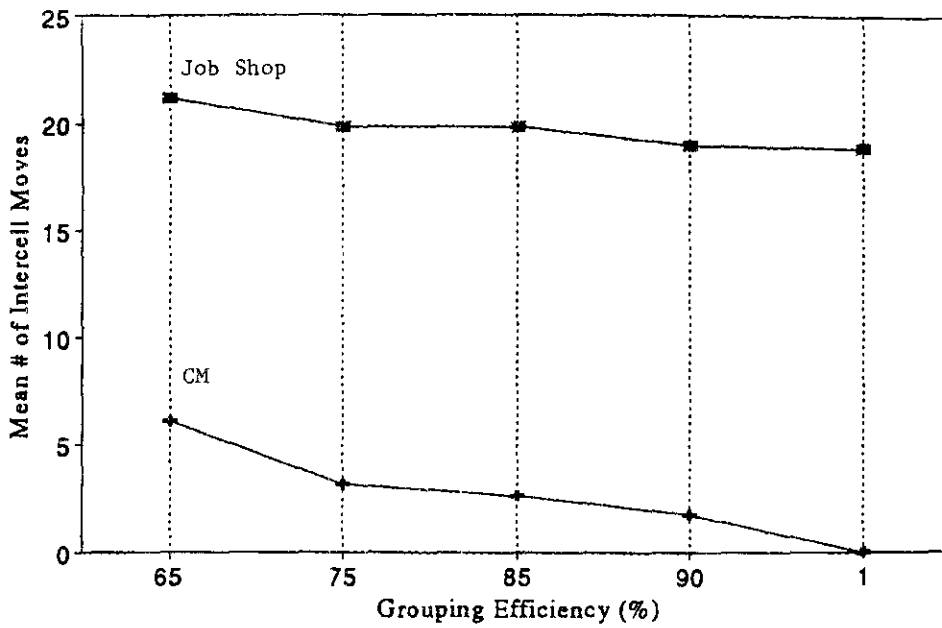


Figure 5. Comparison of mean of intercell moves.

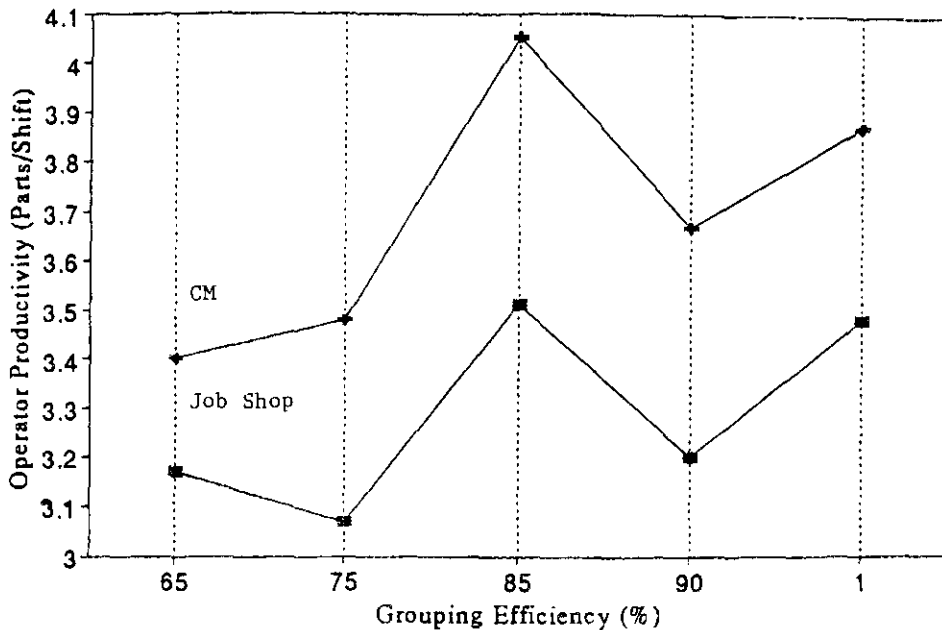


Figure 6. Comparison of mean productivity.

Performance measure	Mean differences of two models and 95% C.I.	Test of hypothesis
Mean flow time	44.2 ± 3.6	Reject H_{0B1}
Mean WIP	5.95 ± 0.65	Reject H_{0B2}
Mean setup time	16% ± 1.8	Reject H_{0B3}
Mean # of intercell moves	27.7 ± 0	Reject H_{0B4}
Mean productivity	3.2 ± 0.25	Reject H_{0B4}

Table 11. Paired-*t* test results for $Q5 = 1.0$.

Shop type	Flow time (hours)	WIP parts	Setup time	Number of intercell moves	Operator productivity parts/shift
Job shop	74.6*	7.47	68.6%	25.6	2.2
	71.2 77.1**	6.8-8.1	58-76	26.1-25.2	2.11-2.29
CM shop	49	5.61	53%	1.48	3.85
	46.9 52.1	4.5-6.4	47-58.2	0.8-2.1	3.78-3.91

Table 12. Simulation results for $Q1 = 0.90$.

Further insight into the comparison of the job shop and CM systems at different $Q1$ levels can be obtained by the graphical presentation of results as depicted in Figs 2-6.

The gradual improvement of performance measures in the CM system as the value of $Q1$ increases is a clear indication that $Q1$ can be used as an effective tool for the evaluation of an M-P matrix. The decision about conversion from job shop to cellular

Performance measure	Mean differences of two models and 95% C.I.	Test of hypothesis
Mean flow time	24.2 ± 5.63	Reject H _{0B1}
Mean WIP	1.75 ± 0.08	Reject H _{0B2}
Mean setup time	15.6% ± 0.09	Reject H _{0B3}
Mean # of intercell moves	24.1 ± 0.06	Reject H _{0B4}
Mean productivity	1.66 ± 0.011	Reject H _{0B5}

Table 13. Paired-*t* test results for $QI = 0.90$.

Shop type	Flow time (hours)	WIP parts	Setup time	Number of intercell moves	Operator productivity parts/shift
Job shop	81*	8	68%	27.8	2.06
	80.5–81.5**	7.4–8.7	58–75.2	26.5–28.7	1.99–2.09
CM shop	66.9	8.6	53%	3.45	3.65
	63.8–68.6	8.3–8.72	47–57.9	2.8–4.1	3.58–3.69

Table 14. Simulation results for $QI = 0.85$.

Performance measure	Mean differences of two models and 95% C.I.	Test of hypothesis
Mean flow time	13.8 ± 1.1	Reject H _{0B1}
Mean WIP	0.5 ± 0.04	Accept H _{0B2}
Mean setup time	14.5% ± 0.07	Reject H _{0B3}
Mean # of intercell moves	24.2 ± 1.2	Reject H _{0B4}
Mean productivity	1.57 ± 0.04	Reject H _{0B5}

Table 15. Paired-*t* test results for $QI = 0.85$.

given in Djassemi (1994). The simulation and paired-*t* test results for this manufacturing situation further demonstrates the usefulness of the procedure.

At $QI = 1.0$, the cellular manufacturing system outperforms the corresponding job shop system in all performance measures (Table 11). When QI drops to 0.90, the simulation and paired-*t* test results are given in Tables 12 and 13. As the results indicate at this QI level the cellular manufacturing system still outperforms the corresponding job shop system in all performance measures. At $QI = 0.85$, the cellular manufacturing system outperforms the job shop system in four out of five performance measures. The simulation results and results for the paired *t*-test are summarized in Tables 14 and 15. As QI drops further, the performance of cellular manufacturing systems deteriorates and it fails to outperform the job shop system in more and more performance measures.

A more comprehensive study of a range of manufacturing systems is required to determine a threshold value of QI for conversion to cellular manufacturing for a general manufacturing situation. Those two numerical examples, however, demonstrate how QI in conjunction with simulation can be used to determine such a threshold value.

5. Conclusions

The procedure presented in this paper can be used to determine the relationship between values of QI and the performance of the corresponding cellular manufacturing system. The simulation results showed that as the value of QI increases, the mean flow time and WIP inventories for the cellular manufacturing system decrease. For high values of QI (close to 100%) the CM system outperformed the corresponding job shop system in all performance measures used in this study. On the other hand, at low values of QI (close to 50%) the job shop outperforms the corresponding CM system. This study shows that QI serves as an effective tool in the evaluation of the M-P matrix for conversion to CM.

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