The cellular manufacturing paradox: a critical review of simulation studies

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Received January 2007
Revised July 2007
Accepted October 2007

Abstract

Purpose – A number of simulation studies have been conducted previously by several researchers, in order to compare the performance of cellular and functional layouts. The purpose of this paper is to highlight the lack of objectivity of a number of these studies, in order to explain the origin of their conflicting conclusions.

Design/methodology/approach – A taxonomy of the main experimental factors and performance measure used in the main simulation comparative studies is followed by a critical assessment of ten of these studies. The analysis is focused on the objectivity of the layout comparison methodologies. Then, the determined shortcomings are categorized and some of them are illustrated by way of simulation.

Findings – The revealed shortcomings are most likely responsible for the conflicting conclusions of the studies and may well explain what is called in the literature the "cellular paradox."

Originality/value – This work sets up the basis for an objective comparison methodology between the two manufacturing system layouts. Such a methodology should in fact be free of all the highlighted objectivity flaws.

Keywords Cellular manufacturing, Group technology, Facilities, Simulation

Paper type Literature review

1. Introduction

The race towards productivity affects all the facets of manufacturing system (MS) design and management. In particular, the layout of manufacturing facilities is one of the main tasks to refine in order to achieve high-performance levels. Since, the middle of the past century and the expansion of the group technology concept an alternative layout pattern has emerged as a substitute for the traditional functional layout (FL) that groups functionally similar machines in separate departments (Burbidge, 1975; Hyer and Wemmerlov, 1989). This layout is the cellular layout (CL) that advocates clustering the machines required to manufacture each family of similar product types into independent cells.

At first, the CL has gained a great popularity among researchers and even some practitioners. An abundant prescriptive literature was devoted to that new layout trend (Ham and Reed, 1977; Hyer, 1984; Burbidge and Dale, 1984; Howard and Newman, 1990).

Journal of Manufacturing Technology Management
Vol. 19 No. 5, 2008
pp. 591-606

1741-038X
DOI 10.1108/17410380810877276

However, many researchers started claiming that the CL may be inferior to the FL under a wide set of conditions (Craven, 1973; Leonard and Rathmill, 1977; Rathmill and Leonard, 1977; Flynn and Jacobs, 1986; Flynn, 1987; Suresh, 1991). These researchers argue that in empirical studies, CLs have generally been favorably compared to poor FLs. They also assert that efficiently-operated FLs are capable of outperforming the CL. Subsequently, a great number of empirical, analytical and simulation studies have been devoted to the FL-CL comparison. Facing the large amount of research papers with diverging conclusions, some researchers synthesized the main streams of literature. Shambu *et al.* (1996) presented a taxonomical review of the studies dealing with the performance evaluation of the cellular MSs. A part of this work covered not only simulation comparative studies that constitute the mainstream of this research field but also a number of analytical and empirical studies. The authors pointed out the "cellular manufacturing paradox" that emerged from a number of conflicting simulation-based studies. They also provided taxonomy of the main experimental factors and performance measures used in these studies before reporting their major findings and conclusions. However, the presented analysis failed neither to explain the cellular paradox nor to highlight the objectivity flaws in many of the covered studies. Agarwal and Sarkis (1998) also reviewed and analyzed a number of CL-FL comparative studies. Again, their work simply reported the major findings of some published works but without any critical objectivity assessment of their methodology.

This research focuses on the simulation-based FL-CL comparative studies. It aims at highlighting the lacks of objectivity of a number of these studies in order to explain the origin of their conflicting conclusions. It also demonstrates some of the discussed shortcomings through simulation. It is organized as follows. The next section presents a taxonomy of the main factors used in the main published simulation studies concerned with FL-CL comparison. The foremost used performance measures are also discussed in this section. Section 3 analyses the findings of a number of relevant studies. In Section 4, these studies are critically reviewed with a special emphasis on the objectivity of their comparison methodologies and the stated shortcomings are categorized. Section 5 illustrates through simulation how one of the findings, presented by one of the cited papers as a general conclusion, does not stand beyond its original limited scope. The final section summarizes the paper and discusses the basis for an objective comparison methodology between the two MS layouts.

2. Taxonomy of existing comparison research

2.1 Main experimental factors

2.1.1 General MS characteristics. The studied MSs are characterized by a number of machines ranging from 12 to 30. These are either arranged into departments or else into manufacturing cells. The number of departments (d) ranges between 4 and 15, whereas the number of cells (c) ranges between 3 and 5. Furthermore, the studied systems were designed for a demand pattern comprising 3-80 product types (t) belonging to a number of families (f) varying from 3 to 10. Each product type requires a number of manufacturing operations (mopt) ranging between 2 and 25. Finally, only two of the treated studies dealt with the labor resources, whereas the others overlooked this factor assuming that a worker is always available whenever he is needed (Figure 1).

2.1.2 Degree of decomposability of the part machine matrix (DD). This factor translates the feasibility of the decomposition of the MS into independent cells.

	Study	# Mach	# Dept	# Cell	# P. type	# Fam	# Labor	#opr / P. type	DD	q	Scheduling rules	Transfer in CL	Flow in CL
1.	Morris and Tersine, (1990)	30	8	5	40	5	NS	2~ 6	High	50	RL	batch	Unidir; Backtrack
2.	Shafer and Charnes, (1992)	15	15	?	30	f(DD)	NS	U (11,25); U (4,10)	Low, Medium, High.	10, 250	?	part	?
3.	Morris and Tersine, (1994)	30	8	5	40	5	14	2 ~ 6	High	50	RL	batch	Unidir
4.	Suresh and Meredith, (1994)	31	10	5	50	5	NS	U(4,6) U(3,6); U(4,7)	High	5, 10, 15, 20, 32, 40, 50, 70, 100.	FCFS, FOR1, FOR2	batch	?
5.	Shafer and Charnes, (1995)	30	8	5	40	5	30; 8	2~6	High	50	FCFS	part	Unidir; Backtrack
6.	Jensen et al., (1996)	30	8	5	80	10	NS	4~8	High	?	FCFS-L; SPT-L; EDD-L; EDD-U	batch	?
7.	Farrington and Nazemetz, (1998)	25	7	4	50	4	NS	?	Medium	25; 60	?	part	?
8.	Faizul huq et al., (2001)	12	4	3	3	3	NS	4	High	35; 40; 45; 50; 55; 60; 65; 70; 75	FCFS	batch	Unidir
9.	Li, (2003)	28	12	4; 5	19	?	NS	4~9	?	?.	RL	part; batch	Backtrack. (4 cells); Unidir (5 cells)
10.	Pitchuka et al., (2006)	8	3	2	4	2	NS	2~5	High	5, 25	FCFS	batch	Unidir

Notes: [*shaded boxes contain variable settings*]
U (Min, Max): Uniform distribution between Min and Max; DD: degree of decomposability of the part machine matrix; f(DD): Function of DD; q: lot size; D: Demand rate; RL: Repetitive Lot; FCFS: First Come First Served; FCFS-L: Limited setup duplication for FCFS; FOR: Family Oriented Rule; EDD: Earliest Due Date; EDD-L: Limited setup duplication for EDD; EDD-U: Unlimited setup duplication for EDD; SPT: Shortest Process Time; SPT-L: Limited setup duplication for SPT; Unidir: unidirectional flow only; Backtrack : backtracking flow allowed; ?: unspecified; NS: Not studied

Figure 1.

The more the product/machine matrix is diagonal the more the decomposability is feasible. The majority of the comparison studies considered very high degrees of decomposability leading to completely independent cells (Figure 1).

*2.1.3 Batch size (*q *)*. In order to reduce the number of the machines setup and transport between work stations, products are generally manufactured and transported in batches. Many authors used the batch size as variable factor and demonstrated that the use of small batch sizes in combination with an efficient scheduling rules results in the improvement of the CL performances (Figure 1).

2.1.4 Scheduling rules. Jobs arriving at a department or a cell may have to wait in a queue until the required machine becomes available. The order in which the jobs are to be processed is generally specified by a scheduling rule or a priority rule such as first come first served (FCFS), shortest process time (SPT), earliest due date (EDD) or repetitive lots (RL). Using the first, jobs are simply selected according to their arrival times whereas the second rule prioritizes the job with the shortest processing time (PT). Alternatively, the EDD rules aims at reducing the number of tardy jobs by prioritizing jobs with the EDDs. The limited versions (-L) of these three rules are often used in order to avoid the duplication of machines set for the same product type. Finally, when the RL rule is used, jobs of the same type that the one just processed are always prioritized in order to avoid unnecessary setups (Figure 1).

2.1.5 Transfer mode. In the FL, the interdepartmental distances are considerable. Hence, products are often transferred by batches or lots in order to reduce the transfer costs. Some studies used this transfer mode in the CL, whereas others exploited the proximity of machines of a same cell to transfer products by part. The "part by part" transfer mode allows simultaneous execution of several operations on the same batch called operations overlapping (Figure 1).

2.1.6 Flow direction. A number of authors included the flow direction within a cell as an experimental factor. This factor has two possible levels: unidirectional flow, or else flow with backtracking allowed. The first level is obtained either by altering product type routings or by duplicating cell machines in order to avoid backtracking (Figure 1).

2.1.7 Processing time (PT) and Set up time (ST). Several studies modeled both times by two independent probabilistic laws. Others formulated ST as a fraction of PT. It is worth noting here that PT is often given for the whole batch and not per part. In Figure 2, we brought these values to the same "per part" scale.

2.1.8 Set up time reduction factor (δ). This factor materializes one of the crucial advantages of the CL and more particularly of the group technology philosophy. Indeed, part types of a same family have usually very similar setups on the machines. Hence, if a machine is set up for a certain type and then it should be set for another type of the same family, the nominal setup time for the second batch should be reduced by the δ factor (Figure 2).

2.1.9 Transfer time (TT). In the FL, this parameter corresponds to the interdepartmental travel time. It is often modeled using appropriate probabilistic laws. On the other hand, within the CL framework, they correspond to the durations of intra cell moves. These times are generally very small compared to those in the FL. This constitutes the second major advantage of CL (Figure 2).

2.1.10 Demand rate. The demand rate is mainly expressed by the batch inter-arrival times (IAT) in the MS. They are generally generated by common probabilistic

	Study	PT (mn)	ST (mn)	δ		TT (mn)		IAT (mn)
				FL	CL	FL	CL	
1.	Morris and Tersine, (1990)	N (41.2,4.5)	PTx0.1; PTx0.5; PT;N (120,100)	0; 0.5; 1	0; 0.5	0.5 miles/h; 5 miles/h	0.5 miles/h; 5 miles/h	420;Exp (420)
2.	Shafer and Charnes, (1992)	U (10, 30); U (1, 5)	U (30, 120)	1	0.586	Neglected	Neglected	?
3.	Morris and Tersine, (1994)	N (41.2,4.5)	N (120,100)	0; 0.5; 1	0; 0.5	5 miles/h	5 miles/h	Exp (420); Exp(360)
4.	Suresh and Teredith, (1994)	Exp (6); Exp (5.4); 3-Erg (6); 3-Erg (5.4)	Exp (180); 3-Erg (180)	1	0.1; 0.2; 0.5; 0.8; 1	U(30,60) & U(15,30)	U(3,6)	Exp ((q/D)*216000); 3-Erg ((q/D)*216000)
5.	Shafer and Charnes, (1995)	N (41.2, 15) ; N (22.66, 8.25)	N (120,100)	0; 0.5	0; 0.5	0; U(15, 60)	0	Exp (600)
6.	Jensen et al., (1996)	Exp (50)	PTx0.5	1	0.1; 0.3; 1	Neglected	Neglected	9.6; Pois (9.6)
7.	Farrington and Nazemetz, (1998)	?	?	1	1	?	?	Exp (?)
8.	Faizul huq et al., (2001)	6	180	1	0.1; 0.2; 0.3; 0.4; 0.6; 0.8; 1	U (20, 60)	U (20, 60)	Exp (6)
9.	Li, (2003)	Gam (6, 1.33); Gam (6, 3); Gam (6, 6.75)	Gam (120, 0.89); Gam (120, 2); Gam (120, 4.5)	0.2; 0.5; 0.7	0.2; 0.5; 0.7	Neglected	Neglected	Exp (?)
10.	Pitchuka et al., (2006)	Various¶ T, U and N distributions	Various¶ T, U and N distributions	0; 0.5; 1	0; 0.5	Neglected	Neglected	15; 20; 25

Notes: [*shaded boxes contain variable settings*]
IAT: Jobs Inter Arrival time; PT: Process Time (per part); ST: Setup Time; δ: Setup reduction factor; TT: Transfer Time; N (A,SD) : Normal distribution with average A and standard deviation SD; U (Min, Max) : Uniform distribution between Min and Max; Exp (A): Exponential distribution with average A; x-Erg: x order Erlang distribution; Gam (A,SD) : Gamma distribution with average A and standard deviation SD; Pois (A) : Poisson distribution with average A; T(Min,Mode,Max): Triangular distribution between Min, Mode and Max; FLP: Part family oriented FL; &: Both settings used together in the same run for ordinary and priority transfers in turn;¶: a different distribution is used for each machine and each part; ?: unspecified

Figure 2.

distributions (Figure 2). Besides, some studies focus only on the stability of this factor without changing its mean.

2.2 Performance measures

Table I shows the main performance measures.

2.2.1 Work in process (WIP). This measure characterizes the fluidity of the part flow in the system. It has mainly been measured in two manners: the number of parts in the system and the time weighted number of parts in the system. The latter is obtained by summing up the average setup and process times of all parts either being processed or waiting in the different MS queues.

2.2.2 Mean flow time (MFT). This performance measure constitutes with work in process (WIP) the most popular measures used in the FL-CL comparative studies. It also characterizes the fluidity of the part flow in the system. For each part, the flow time is simply obtained by subtracting the exit time from the entry time.

2.2.3 Due date-related measures. Mainly, researchers used mean tardiness (MT) and mean earliness (ME) as due date related performance measures. The first is taken as the average, over all tardy jobs, of the difference between actual delivery date and the promised due date. ME is obtained by analogy for all early jobs. Some researchers also use the percentage of tardy jobs and the percentage of early jobs without taking into account the actual amount of tardiness or earliness.

2.2.4 Other measures. The system throughput is usually considered as productivity measure. It is the average number of parts exiting the system by time unit. It is the main indicator used for detecting the attainment of steady state in a simulation run. Also, some studies use the average machine utilization rate, the operator utilization rate, the average ST/PT ratio or the mean "queue" waiting time as performance indicators. Maximizing the first two measures ensures a high degree of resource exploitation, whereas minimizing the third or the fourth measure enhances the efficiency of the MS piloting.

3. Analysis of the studies findings

3.1 Proper analysis factors

Many of the factors cited in the previous section are not suitable for a proper comparison between FL and CL. In fact, basing the comparison on the ST factor independently of the PT factor is meaningless. Actually, what really matters is the

Table I.
Main performance measures

Study	WIP	MFT	MT	ME	Through-put	Machine utilization	Operator utilization	(ST/PT) ratio	Queue time
1	X	X							
2	X	X							
3	X				X	X	X		
4	X	X				X			
5	X	X							
6	X	X	X	X					
7	X	X	X			X			
8		X			X				
9	X	X						X	
10									X

relative importance of the setup time compared to the PT since one of the main advantages of implementing CL is the potential savings in setup times. If ST is very low compared to PT, then the anticipated savings could be very low and the situation would be favorable to FL. Hence, an appropriate simulation-based comparison study should feature the ratio ST/PT as an experimental factor instead of the two factors ST and PT independently. Following the same logic and since the setup is performed for each batch and not for each part, the batch size q is a key factor that should be considered in a proper simulation-based comparison study. This parameter even permits one to formulate a more significant factor in which the denominator is multiplied by the batch size: $ST/(PT \cdot q)$. The preceding analysis could be applied to the transfer time (TT) compared to the PT. Therefore, the study should also feature the ratio TT/PT or also $TT/(PT \cdot q)$ as an experimental factor.

Furthermore, one of the main benefits of FL is the synergy between functionally equivalent machines of a same department. In fact, if the overall utilization rate of the MS is very low, this advantage may be unexploited and the CL will be indirectly advantaged. So, a factor controlling the MS congestion level is also required. The job IAT is commonly used for this purpose.

Additionally, three other factors should be considered in an objective simulation-based comparison study. These are the transfer mode (overlapping), the ST reduction factor (δ) and the scheduling rule. As discussed in the previous section, specific setting of these factors could represent some of the main potential benefits of group technology and hence, of the CL.

As for the remaining factors, it is preferable to keep them constant thought the experimental plan to ensure objectivity. In fact, the DD should be kept constant at a fairly high level to ensure the feasibility of the CL and all the other factors could be fixed at any particular level not biasing any of the studied layouts.

3.2 FL and CL superiority contexts

Among the ten covered studies, seven studies determined both CL and FL superiority contexts; two studies exclusively established FL superiority contexts, whereas one study concluded that CL is always the best performing layout. Tables II and III, in turn, depict the CL and FL superiority contexts expressed as a combination of the factors discussed in the previous analysis. The remainder of this section details the findings of each study in turn.

Morris and Tersine (1990) examined the influence of some operational parameters on the performance of CLs compared to FLs. In that comparative study, the performances were assessed using the mean flow time (MFT) and WIP while varying the ratio of setup to process time, the TT, demand stability and flow work within cells. In the quasi totality of the tested contexts, the FL always generated smaller MFT and WIP (Table II). It appeared from their results that an ideal context for CL is characterized by a high ST/PT ratio, a stable demand, a unidirectional material flow and a substantial average TT between process departments (Table III).

Shafer and Charnes (1992) assessed the suitability of CL under a variety of operating conditions defined by combinations of DD, mopt, PT and q. They used the same performance measures as the previous study. However, they compared a FL characterized by 15 single-machine-departments to a CL in which the 15 machines were

Table II.
CL superiority contexts

Study	Contexts[a]	ST/PT	TT/PT	Q	Rule	IAT	Overlap	δ
1	1	1	[c]–	50	RL	Exp (420); 420	No	0; 0.5
2	1	3.75; 25	Neglected	10; 250	[c]–	[c]–	Yes	0.586
4	5	$30^{(1,2,3)}$; $33.33^{(4,5)}$	$0.75^{(1,2,3)}$; $0.83^{(4,5)}$	5; 10; 15; 20; 32; 40; 50; $70^{(2,4,5)}$	FCFS	Exp $((q/D)*216{,}000)^{(1,2,4)}$; 3-Erg $((q/D)*216{,}000)^{(3,5)}$	No	0.1; 0.2; $0.5^{(2,5)}$; $0.8^{(5)}$
5	4	$2.91^{(1,2)}$; $5.29^{(3,4)}$	$0^{(1,3)}$; $0.91^{(2)}$; $1.65^{(4)}$	50	FCFS	Exp (600)	Yes	0; 0.5
7	3	Low $PTV^{(1,2)}$; high $PTV^{(3)}$	Low $PTV^{(1,2)}$; high $PTV^{(3)}$	25; 60	[c]–	Low $DV^{(1)}$; high $DV^{(2,3)}$	Yes	1
8	3	30	6.66	40; 50; $55^{(1,2)}$; $60^{(1)}$	FCFS	Exp (6)	No	$0.1^{(1)}$; $0.2^{(2)}$; $0.3^{(3)}$
9	1	20	Neglected	1; [c]–	RL; SPT; FCFS	Exp ([c])	Yes; No	0.2
10	1	Various[b]	Neglected	5	FCFS	20; 5	No	0; 0.5

Notes: [a]The number of contexts where CL is superior to FL; [b]a different value is obtained for each machine and each part; [c]–unspecified; superscript $^{(i)}$ indicates that the value belongs to the study context *i* (a value with no superscript belongs to all of the study contexts); PTV – processing time variability; DV – demand variability

Study	Contexts	ST/PT	TT/PT	Q	Rule	IAT	Overlap	δ
1	6	2.91$^{(1,5,6)}$; 0.1$^{(2)}$; 0.5$^{(3)}$; 1$^{(4)}$	^{b}, ^{e}–	50	RL	Exp (420)$^{(1,2,3,4,5)}$; 420$^{(6)}$	No	0; 0.5; 1
3	1	2.91	^{b}–	50	RL	Exp (420); exp(360)	No	0; 0.5; 1
4	2	30	7.5 and 3.75^{d}	32$^{(1)}$; 40$^{(1)}$; 50$^{(1)}$; 70$^{(1)}$; 100$^{(2)}$	FCFS	Exp ((q/D)*216,000)	No	0.1$^{(2)}$; 0.2$^{(2)}$; 0.5$^{(2)}$; 0.8$^{(2)}$; 1
5	2	5.29	0; 1.65	50	FCFS	Exp (600)	Yes	0; 0.5
6	2	0.5	Neglected	?	SPT-L; EDD-U	9.6; Pois (9.6)	No	0.1; 0.3; 1
7	4	(Low PTV$^{(1,3)}$)^{b}; (high PTV$^{(2,4)}$)^{b}	Low PTV$^{(1,3)}$; high PTV$^{(2,4)}$	25, 60	^{b}	Low DV$^{(1,2)}$; high DV$^{(3,4)}$	Yes	1
8	4	30	6.66	35; 40$^{(4)}$; 50$^{(4)}$; 55$^{(3,4)}$; 60$^{(2,3,4)}$; 65; 70; 75	FCFS	Exp (6)	No	0.1$^{(1)}$; 0.2$^{(2)}$; 0.3$^{(3)}$; 0.4$^{(4)}$; 0.6$^{(4)}$; 0.8$^{(4)}$; 1$^{(4)}$
9	1	20	Neglected	1; ^{b}–	RL, SPT, FCFS	Exp (^{b})	Yes; no	0,5; 0.7
10	1	Various^{d}	Neglected	5; 25	FCFS	15;20;25	No	0; 0.5; 1

Notes: ^{a}The number of contexts where FL is superior to CL; ^{b}unspecified; ^{c}both settings used together in the same run for ordinary and priority transfers in turn; ^{d}a different value is obtained for each machine and each part; ^{e}ten times the unspecified value (^{b}) of TT/PT; superscript $^{(i)}$ indicates that the value belongs to the study context i (a value with no superscript belongs to all of the study contexts); PTV – processing time variability; DV – demand variability

Table III.
FL superiority contexts

divided between a number of cells directly dependent on DD. The authors found the CL superior to the FL in all operating conditions according to both performance measures.

Morris and Tersine (1994) investigated the impact of a dual resource constrained shop on the performances of CL and FL using three operator-scheduling rules in the CL. It appeared from their results that FL outperformed CL with regard to the mean throughput, the WIP, the machine and the operator utilization rates regardless of the operator-scheduling rule. In order to investigate the sensitivity of their results to changes in shop congestion, authors changed, respectively, the job inter arrival time and the worker utilization level in two other experiments. FL persistently outperforms the CL.

Suresh and Meredith (1994) searched means of overcoming the loss of pooling synergy in CL. They used simulation in order to compare the CL to an efficiently operated FL (EFL) using the WIP and MFT performance measures together with the average machine utilization rate. The EFL, originally introduced by Suresh (1992) in order to avoid biased comparison in favor of CL, is characterized by an optimal q, by reduced TT and by part family oriented scheduling rules. The main experimental factors involved in this study were PT, ST, q, δ and IAT. They were tested separately and then combined. Hence, the FL was found to be superior to the CL for large lot sizes ($q > 32$). However, for relatively small q, the CL could outperform the FL if δ is smaller than 0.2. This situation did not change when the variability of PT, ST or IAT were separately reduced. Nevertheless, when the effects of all factors were combined, the CL outperformed the FL even for small lot sizes.

Shafer and Charnes (1995) used simulation in a manufacturing context very similar to the one of Morris and Tersine (1990) regarding the number of part types and families, machines, cells, departments, and operations per part type. Their aim was to compare alternative loading procedures for CL and FL in a variety of operating environments. These are defined by combinations of 4 factors: flow mode, TTs, labor constraints and MS congestion level. It is worth noting here that the latter was modeled through the variation of the PT. In addition, each of the layouts is investigated in accordance to two loading policies. For the FL the first policy permitted machine dedication whereas the second did not. On the other hand, for CM the first policy authorized processing only one job at a time in a cell and the second permitted multi-job processing. Both policies authorized CL job overlapping. The authors used the *MFT* and *WIP* performance measures in a two stage comparison methodology. In the first, where the labor constraints were not considered, the CL performed better than the FL regarding the *MFT* while all systems were found to be equivalent regarding *WIP*. In the second stage, a constraint was imposed on labor allowing only 8 operators to the whole shop in both configurations. It is worth noting here that the presence of one operator is required not only during setups, but also during processing operations. In this situation the FL showed lower *MFT* than the CL. The authors explained this by the fact that the labor constraints handicaps more seriously the CL since it diminishes the overlapping possibilities while it has a little effect on the FL since the departments have only 3 machines in average.

Jensen *et al.* (1996) compared the FL and the CL using *MFT*, *WIP* and three due-date-related performance measures namely *MT*, *ME* and the percentage of tardy jobs. They also studied a hybrid layout in which the MS is divided into 2 cells each of them manufacturing some of the product types. This hybrid layout is not treated in the present study. They used a full- factorial experimental plan involving 3 experimental factors other than the layout type. These are the scheduling rules, demand variability and the setup reduction factor δ. Their results were first analyzed by ANOVA in order to determine the influence of each factor on each studied performance measure. Aside from the layout type, the most prominent factor was found to be the demand variability followed by the setup reduction and the scheduling rules. Then, a pairwise comparison of the scheduling rules was performed. SPT-L and EDD-U were determined as the best performing rules regarding MFT and MT, respectively. Finally, they compared layouts using the best found scheduling rules. This final step revealed that the FL was always superior to the CL with regard to all performance measures.

Farrington and Nazametz (1998) based their comparative study on a three-factor-full-factorial experimental plan. This plan encloses the layout type, the *PT* variability and the *IAT* variability as experimental factors. Let's mention here that the high variability level was associated to a small lot size and vice versa. They utilized a large number of performance measures, namely *MFT*, *WIP*, the percentage of tardy jobs, the average machine utilization rate and a number of other less commons measures. The FL was found to be superior to the CL when *PT* variability is high and *IAT* variability is low. But, when both factors show high variability, the performances of the two layouts are close. Besides, The CL outperforms the FL in all remaining conditions.

The study of Faizul *et al.* (2001) presented a straightforward two-factor-full-factorial simulation plan for FL-CL comparison using the *MFT* and the throughput performance measures. The two factors were q and δ**???**In addition, the authors used the efficiently operated FL (EFL) concept for more objectivity. ANOVA investigation showed significant differences between the two layouts in some of the studied combinations only in terms of *MFT*. Throughput performances were not significantly different. Hence, The CL outperformed the FL only for small lot sizes and very important *ST* reduction. In all other conditions, the FL was noticeably superior.

Li (2003) tried to establish the superiority domains of both layouts in a variety of contexts defined by, the flow direction, the transfer type, the variability of *PT*, the variability of *ST* and finally the *ST* reduction factor. The author made the cell unidirectional flow possible by duplicating the necessary machines to avoid backtracking. This indirectly led to the reduction of the cell number. The *MFT* and *WIP* results analysis showed that the prominent factor in establishing the superiority of one of the layouts is the setup reduction factor. In fact, the CL outperformed the FL when $\delta$was set at the high level and the FL was the best layout in the low δ region. For intermediate value δ, both layouts were equivalent.

Pitchuka *et al.* (2006) compared FL to CL using a four-factor-full-factorial experimental plan. This plan includes *PT*, *ST*, q and *IAT* as experimental factors. They considered only the "queue" waiting time as performance measure. It was shown that CL can outperform FL under several conditions. Indeed, numerous work centers "queue" times in the CL were found to be inferior to those of the corresponding work centers in the FL.

4. Objectivity assessment

Morris and Tersine (1990, 1994) considered very low TTs which implicitly advantage the FL, since one of the main advantages of CL is the time saving by locating machines required to process one job close to each other. On the other hand, they used a perfectly decomposable part/machine matrix which implicitly advantages the CL. In fact, this situation involving no job transfer between cells is very unusual. Also, despite the fact that the influence of the lot size on the performances of MSs is established, this factor was not included in their experimental design. Moreover, the batch size was not explicitly mentioned by the authors but it was retrieved from other related studies. Finally, the authors used a CL with no overlapping allowed in job processing. This does not permit to perceive full CL benefits.

The study of Shafer and Charnes (1992) is unmistakably biased in favor of the CL. In fact, by considering single-machine departments, the authors abolished the main and probably the only benefit of this type of layout: the pooling synergy effect between same department machines. Hence, as it could be predicted, the results were clearly in favor of the CL despite the assumption of null TTs advantaging the FL. Finally, the demand pattern has not been characterized since the batch IAT was not revealed by the authors.

Suresh and Meredith (1994) used FL TTs that are relatively very high compared to the PTs. This advantageous condition for the CL is probably responsible for its performance being superior to the performance of the FL in practically all the testing contexts despite the fact that no job overlapping has been used in the CL. In addition, the authors used a perfect cellular environment with no intercellular transfers allowed which is barely realistic. This factor is also responsible for boosting the relative performance of the CL compared to the FL.

Shafer and Charnes (1995) found that the only factor responsible for the superiority of one layout or the other was the volume of the labor workforce. This conclusion should be restricted to the context defined several fixed factors such as their "unusual" managing policy. In fact, in their MS, processing parts requires the uninterrupted presence of an operator. This restrictive assumption holds only in some special manufacturing cases. Results could be completely different if this assumption is dropped or if some non-investigated factors, such as the lot size, were set at different levels.

Despite its established importance, Jensen *et al.* (1996) did not use the lot size as an experimental factor neither did they mention its constant value used throughout the investigation. In addition the authors used twofold-biased conditions in favor of the FL. First, they neglected the TTs. This assumption is sound in the CL context but far from realistic in the FL. Second, no job overlapping was permitted. Combined with an appropriate lot size this factor could reverse the superiority order in favor of the CL. Finally, in the third and final analysis step, the layouts were compared using the same scheduling rule. This rule was previously determined as the one offering the best overall performance. A better comparison would be carried out with each layout featuring its best specific scheduling rule.

The main shortcoming of the study carried out by Farrington and Nazametz (1998) is that it failed to report vital information about the used experimental factor settings as well as the other key elements defining the manufacturing contexts. Among these elements one can cite, the scheduling rules, mopt, ST and PT. Also, no technical simulation-related information such as the replication and the warm-up period lengths was reported. More importantly, the authors stated that they willingly chose not to reduce the ST in the CL context. Their motivation was to avoid any biases in favor of the CL.

But, by doing so, they favored the FL since they eliminated one of the strongest advantages of the CL. Finally, the rationales behind the large number of uncommon performance measures used by the authors are not clear.

The major weakness of the study by Faizul *et al.* (2001) is the definition of the manufacturing context. In fact, they used the same routings for the same product types. This generated three identical manufacturing cells. More gravely, the use of single-product families annuls any setup operation in the cell except for the initial setups. Hence, the setup reduction factor becomes irrelevant and any results showing the importance of this factor are seriously questionable. In addition, despite stating that no inter-cell moves were allowed, the authors defined the inter-cell travel time by a uniform law.

Concerning the study of Li (2003), the machine duplication within cells could be a biases source favoring CL. In fact this could add to the CL one of the major advantages of the FL, which is the synergy between functionally equivalent machines.

In their study, Pitchuka *et al.* (2006) used conditions biased in favor of the FL. They considered very low TTs in the FL and they did not permitted job overlapping in the CL. In addition, the authors considered a MS including two machines of the same type in one cell. Table IV summarizes all the reported shortcomings.

5. Illustration

In this section, simulation is used to illustrate one of the facets of the cellular manufacturing paradox in one of the main published studies (Morris and Tersine, 1990) used hypothetical shop data featuring 40 product types belonging to five families and 30 machines divided between eight process departments in the FL and five cells in the CL. Each part type required two to six manufacturing operations. The CL configuration did not permit either job overlapping between same cell machines or job transfer between cells. Also, a setup reduction factor of 0.5 was utilized when a job of different type but from the same family is processed on the same machine. In both layouts, the queues were governed by the RL priority rule. This section focuses on the results they obtained with their model characterized by a setup time governed by a normal law $N(120,100)$ min, a constant 420 min batch IAT, a high-material handling speed and backtracking allowed within cells.

		Studies									
		1	2	3	4	5	6	7	8	9	10
Conditions favoring FL	Null or very low TT	X	X	X			X				X
	No overlapping	X		X			X				X
	No setup reduction							X			
Conditions favoring CL	Very high DD	X		X	X						
	Single-machine departments		X								
	Very high TT				X						
	Machine duplication									X	X
Others	Important factor not included in investigation	X		X		X	X				
	Lack of important data		X				X	X			
	Inappropriate MS data								X		

Table IV. Main shortcomings

The investigation was carried through a simulation model developed using the commercial discrete event simulation tool Arena (Jerbi *et al.*, 2006; Kelton *et al.*, 2002; Arena, 2002). The first step of the investigation consisted in retrieving the same results proclaimed by the authors for the cited conditions. This was achieved with a very good precision (less than 1 percent). The same replication number and length were adopted and the same warm up period was also used (Table V).

Then, we dropped the assumption of no job manufacturing overlapping in the CL. Hence, we allowed the batches of 50 parts to be simultaneously manufactured by several machines of several and to be transferred by unity. The results show that the CL becomes superior to the FL since its MFT is 63 percent lower than the one of FL after it was 12 percent higher in the study of Morris and Tersine (1990) (Table V).

The third and final phase of our simulation aimed at verifying if the results obtained in phase II were dependent on the lot size (50) taken in that phase. We tried two values of q which are, respectively, the half and the double of the original value. The same superiority trend is conserved. Hence, unlike the conclusion of Morris and Tersine (1990), The FL outperforms the CL only when job overlapping is not allowed and this, independently of the lot size.

6. Conclusion and future work

This paper focuses on the simulation-based FL-CL comparative studies. It presents a taxonomy of the main factors used in the main published simulation studies concerned with FL-CL comparison. It also mentions several objectivity flaws in a number of these studies in order to explain the origin of their conflicting conclusions. These are either conditions favoring the FL or the CL or other conditions such as not including some important factors in the investigation, a lack of important data or even inappropriate MS data. The paper also illustrates through simulation how one of the findings, presented by one of the cited papers as a general conclusion, does not stand beyond its original limited scope.

Undergoing work is focused on establishing an objective simulation-based comparison methodology. Such a methodology should avoid all the flaws mentioned in this paper. It is based on the Taguchi method for robust experimental design.

Table V. Simulation results (MFT)

Phase I: validation			
Simulation model		MFT_{FL}	MFT_{CL}
Morris and Tersine (1990) – with no overlapping and $q = 50$		8,249	9,203
Present Study – with no overlapping and $q = 50$		8,222	9,124
Phase II: overlapping effect			
q	MFT_{FL}	*Overlapping*	MFT_{CL}
50	8,222	Not allowed	9,124
		Allowed	3,009
Phase III: lot size and overlapping effects			
q	MFT_{FL}	*Overlapping*	MFT_{CL}
25	4,384	Not allowed	4,771
		Allowed	1,806
100	15,922	Not allowed	17,899
		Allowed	5,429

The conclusions issued from such a methodology should be very strictly bounded to their validity domains and are to be incorporated in a decision-aiding tool.

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