Comparing functional and cellular layouts using simulation and Taguchi method

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Abstract

Purpose – A number of simulation studies were conducted by several researchers in order to compare performances of cellular and functional layouts. The methodologies used by these studies either present several objectivity lacks or are highly time-consuming. The purpose of this paper is to propose a novel and objective methodology, based on the coupling of simulation and the Taguchi method.

Design/methodology/approach – Simulation models for both layouts are first developed. Simulations are then conducted following a standard Taguchi orthogonal array. Subsequently, the obtained results are analyzed using the analysis of variance technique. Finally, a mathematical model is built, and validated by the confirmation test.

Findings – The proposed comparison method permitted to obtain a valid mathematical model used to predict the superiority rank of the two layouts within the scope of the paper.

Originality/value – This paper presents a novel objective methodology for comparing functional and cellular layouts.

Keywords Cellular manufacturing, Manufacturing systems, Simulation, Taguchi methods

Paper type Research paper

1. Introduction

There have been concerted efforts to improve the productivity of manufacturing systems (MS) by introducing new technologies. Cellular manufacturing is one of such technologies. Since its apparition, cellular layout (CL), an application of the group technology concept, has emerged as the best substitute for the traditional functional layout (FL). Unlike the FL that groups functionally similar machines into separate departments, the CL clusters the machines required to manufacture each family of similar product types into independent cells. Analytical models and empirical research have often been used to compare the two MS layouts. Although, the major part of the literature dedicated to FL-CL comparison is based on simulation modeling.

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In the last decades, several simulation studies have focused on FL-CL comparison. Methodologies used by these studies vary widely but can be classified into three groups. In the first group, some authors have employed the one-factor-at-a-time method. In this method, the two layouts are first compared for one manufacturing context considered as a "base model". Then, different experiments are carried out in order to test the robustness of the layout choice obtained in the base model. The testing procedure is based on the alteration of some operating factors, one factor at a time (Morris and Tersine, 1990, 1994). In the second group, some other authors have investigated the effects of the studied factors considering only some specific combinations of their settings. The choice of these combinations was not quite justified. This group includes different comparison studies such as Suresh and Meredith (1994), Huq *et al.* (2001) and Li (2003). In the third and final group, researchers carried out full factorial designs including all the factors to study. Shafer and Charnes (1992, 1995), Jensen *et al.* (1996), Farrington and Nazemetz (1998) and Pitchuka *et al.* (2006) comparison studies belong to this group. Methodologies of the first two groups lack objectivity in the choice of the experimentation conditions. Hence, they do not permit to attach any statistical level of confidence to their conclusions. In addition, no information about factor interaction could be obtained from such methods. On the other hand, full factorial design methodology is highly time consuming and impracticable when the number of factors to study is high.

Accordingly, none of these comparison studies can effectively help the MS mangers in their effort to reliably adopt one of the two layouts or to evaluate the pertinence of migrating from the existing layout to the other. Hence, this research focuses on the development of an objective FL-CL comparison methodology that could fulfill this imperative need of MS managers. In fact, the presented methodology, based on the Taguchi method (TM) for design of experiments and discrete event simulation, could be easily applied to any manufacturing context. It also provides trustworthy results with a minimum experimentation effort.

The remainder of this paper is organized as follows. The next section gives a general presentation of the TM and its major steps. Section 3 depicts the main parameters defining the MS layouts to be compared. Section 4 deals with the application of the TM to layout comparison.

2. Taguchi method

The objective of the TM is to obtain a more robust processes/product under varying environmental parameters. Unlike the full factorial design method that investigates every possible combination of processes parameters, the TM studies the entire parameter space with a minimum number of experiments. Accordingly, the studied process should be characterized by a number of parameters: signal factors (SFs), control factors (CFs) and noise factors (NFs) (Figure 1).

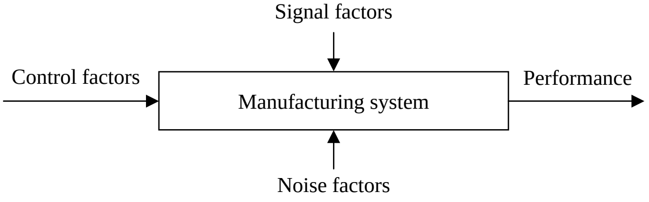


Figure 1.
MS parameters

SFs are parameters that define the study context. They are kept constant. On the other hand, CFs are the factors to be investigated. They are varied throughout the experimentation plan. Finally, NFs are factors difficult, expensive, or impossible to control during the studied process. The process should be robust with regard to the effects of these factors (Phadke, 1989; Ross, 1996). Hence, this method is based upon the technique of orthogonal arrays (OA) which are specially designed experiment plans allowing to simultaneously capture the effects of several CFs (Bagchi, 1993).

Also, the TM normally includes the expression of the results using the signal to noise ratio (S/N). This ratio is an essential indicator of the ability of the system to perform robustly in the presence of some noise effect (Park, 1998). In fact, each experiment of the OA should be repeated several times for the sake of capturing the noise effect. The S/N ratio is used to consolidate the measures issued from these repetitions into a single value (Haldar and Mahadevan, 2000).

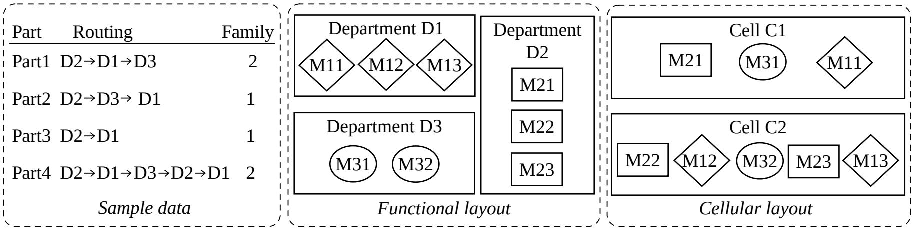
In addition to the OA and to the S/N ratio, TM makes use of the analysis of variance (ANOVA) technique (Montgomery, 2001; Miller, 1985). The ANOVA technique establishes the relative significance of parameters in terms of their percentage contribution to the process response using the statistical F-test. This is accomplished by subdividing the total variability of the S/N ratios, into the sum of the contributions imputed to the parameters as well as the "Error" (Phadke, 1989; Ross, 1996).

The first step of the application of the TM is the identification of the MS parameters. The parameter levels are then selected. Next, the appropriate OA is selected and the MS's parameters are assigned to the OA columns. Simulations are then run based on the arrangement of the OA. Following, results are analyzed using ANOVA. Finally, the mathematical model is developed and subjected to a confirmation test. In the framework of the present study, the confirmed model could be exploited by the MS manager to predict the superiority rank of the two layouts within the scope of the study.

3. Manufacturing system parameters

3.1 Signal factors

According to the FL, the shop is composed of (d) departments D_i ($i = 1, \ldots, d$) each of them include M_n functionally equivalent machines. In this layout, parts move through departments according to their production routings. In this layout, machines are not dedicated to part types (Figure 2). In contrast, the CL is based on the group technology that capitalizes on similar and repetitive activities. Indeed in this layout, the MS is composed of (c) independent manufacturing cells C_j ($j = 1, \ldots, c$). Each one of these cells is a cluster of M_f different machines dedicated to a number of similar part types, called part family (Figure 2). Furthermore, the MSs are designed for a demand pattern



Part	Routing	Family
Part1	D2→D1→D3	2
Part2	D2→D3→ D1	1
Part3	D2→D1	1
Part4	D2→D1→D3→D2→D1	2

Figure 2. Functional and CLs general structure

comprising *p* part of *t* types belonging to a number of families identical to the number of cells *c*. Each product type requires a number of manufacturing operations *mopt*.

3.2 Control factors

All the factors included in this category are controllable by the operators or the plant managers. CFs are varied during simulations in order to investigate the superiority domains of the two studied layouts. Based on the findings of Chtourou *et al.* (2008), seven CFs were selected. The first CF is the ratio of set up time (ST) over the processing time (PT). The second CF, is TT/PT, TT being the transfer time corresponding to the interdepartmental travel time in FL and to the durations of intra-cell moves in CL. ST, PT and TT are generally modeled using adequate probabilistic laws. In addition, part types of a same family have usually very similar set ups on the machines. Hence, if machine is set up for a part type and then must be set up for another type of the same family, the nominal ST for the second job should be weighed by the third CF, namely the ST reduction factor δ. Also, jobs enter the MS in batches following an inter-arrival time (IAT) distribution which is the fourth CF, generated by a common probabilistic distribution. The size of these batches (BS) is the fifth CF. Besides, in both layouts, every job may have to wait in a queue until the required machine becomes available. The scheduling rule (RULE) governing the different queues is the sixth CF in the present study. It could be "First Come First Served" (FCFS), "Repetitive Lots" (RL) or any other sequencing rule (Flynn, 1987; Suresh and Meredith, 1994; Huq *et al.*, 2001). Finally, once processed, every job must be transferred to the next work station in its routings. In the FL, jobs are often transferred by batches 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 jobs by part. The "part by part" transfer mode allows simultaneous execution of several operations on the same batch parts called operations overlapping. This is the seventh CF named (OVER).

3.3 Noise factors

The values of some parameters such IAT or ST are not deterministic. It could be subjected to some variations due to incontrollable factors related to the human or the physical resources of the MS. These variations can influence the performances of the MS. Modeling these parameters using appropriate probabilistic laws accounts for their stochastic aspect.

3.4 Performance measures

The most popular measures to assess the performances of MS are the mean flow time (MFT) and the work in process (Chtourou *et al.*, 2008). These two measures characterize the fluidity of the material flow in the system. Hence, the ratio of MFT of both layouts (MFT_{FL}/MFT_{CL}) is considered in this study for comparison purpose. Also, the throughput, which is usually considered as a productivity measure, is here utilized to characterize the attainment of simulation steady state.

4. Application

4.1 Experiments planning

In this section, we illustrate the application of the comprehensive comparison methodology through the same example treated by Pitchuka *et al.* (2006). In this example, the MS is characterized by four parts types grouped in two families and eight machines divided into three process departments in the FL and into two cells in the CL. Every part family is composed of two part types. Each part type requires an average of four operations/part. Besides, no inter-cell moves are required. As for CFs, they are here studied with two levels each as depicted in Table I. In addition to the considered seven CFs, several factor interactions could also be investigated. The selected interactions are:

$$\left(\frac{\mathrm{ST}}{\mathrm{PT}}\right)\times\left(\frac{\mathrm{TT}}{\mathrm{PT}}\right),\quad \left(\frac{\mathrm{ST}}{\mathrm{PT}}\right)\times \mathrm{BS},\quad \mathrm{IAT}\times\mathrm{RULE},\quad \mathrm{RULE}\times\mathrm{OVER},$$
$$\mathrm{BS}\times\left(\frac{\mathrm{TT}}{\mathrm{PT}}\right)\quad\text{and}\quad\left(\frac{\mathrm{ST}}{\mathrm{PT}}\right)\times\delta.$$

Every two level factor has 1 degree of freedom (DOF) (number of levels − 1). Besides, every two-level factor interaction has 1 DOF [(number of levels of the first factor − 1) × (number of factors of the second level − 1)]. Hence, the total DOF required for the studied seven factors and six interactions is 14 [$= 7\times(2-1)+6\times(2-1)\times(2-1)+1$]. So, a two-level OA with at least 15 DOF was to be selected. The $L_{16}(2^{15})$ OA was thus selected for the present analysis. This array having 15 DOF requires 16 experimental runs and has 15 columns. The factors were assigned to the $L_{16}(2^{15})$ OA using the specified linear graph (Figure 3). A linear graph is a graphic representation of the relation between the studied factors and interactions (Bagchi, 1993; Taguchi *et al.*, 1989). The obtained OA is shown in Table II.

4.2 Simulation

The FL and CL simulation models of the given MS developed by Jerbi *et al.* (2006, 2009) are here utilized. Theses models are developed using the ARENA commercial software (Rathmell and Sturrock, 2002; Kelton *et al.*, 2002). Observations were collected for two performance measures: throughput and MFT. The simulation model is assumed as a non-terminating system, so a steady-state analysis is done using the throughput. This analysis demonstrates that the warm-up period length is 200,000 min. The models are then run for 800,000 min.

	Factors						
Levels	ST^a/PT^a	TT (mn)/PT^a	IAT (mn)	BS	δ	OVER	RULE
1	ST_1/PT_1	$U(1,3)/PT_1$ (for CL) $U(1,9)/PT_1$ (for FL)	15	5	0.5	With overlapping	RL
2	ST_2/PT_1	$U(3,9)/PT_1$ (for CL) $U(3,27)/PT_1$ (for FL)	25	25	0.8	Without overlapping	FCFS

Notes: [a] A different distribution is used for each machine and each part; PT_1, the low level of PT used by Pitchuka *et al.* (2006); ST_1, the low level of ST used by Pitchuka *et al.* (2006); ST_2, the high level of ST used by Pitchuka *et al.* (2006); *U* (Min, Max): uniform distribution between Min and Max

Table I. Control factors

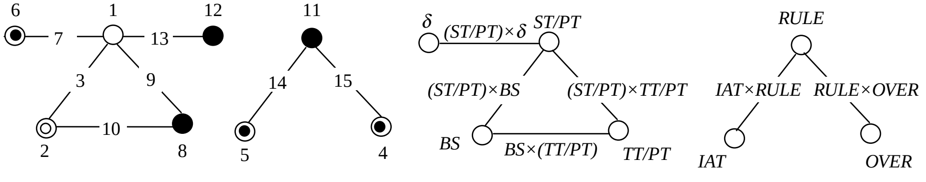


Figure 3. Linear graph for $L_{16}(2^{15})$ OA

Table II.
OA and results

			OA						Results	
								MFT_{FL}/ MFT_{CL}		
Exp	ST/PT (1)	BS (2)	OVER(4)	IAT (5)	δ (6)	TT/PT (8)	RULE (11)	Rep1	Rep2	S/N
1	1	1	1	1	1	1	1	1.82	1.82	5.20
2	1	1	1	1	1	2	2	0.97	0.89	−0.69
3	1	1	2	2	2	1	1	0.82	0.82	−1.74
4	1	1	2	2	2	2	2	1.04	1.03	0.30
5	1	2	1	1	2	1	2	0.06	0.06	−24.96
6	1	2	1	1	2	2	1	1.04	1.04	0.34
7	1	2	2	2	1	1	2	0.94	0.96	−0.45
8	1	2	2	2	1	2	1	0.79	0.77	−2.19
9	2	1	1	2	1	1	2	0.93	1.21	0.35
10	2	1	1	2	1	2	1	1.88	1.92	5.59
11	2	1	2	1	2	1	2	0.14	0.14	−17.12
12	2	1	2	1	2	2	1	0.77	0.77	−2.31
13	2	2	1	2	2	1	1	1.06	1.07	0.56
14	2	2	1	2	2	2	2	0.11	0.12	−19.10
15	2	2	2	1	1	1	1	0.83	0.82	−1.65
16	2	2	2	1	1	2	2	0.98	0.98	−0.19

4.3 S/N-*based ANOVA*

There are three types of *S/N* ratios: lower-the-better, nominal-the-best, and higher-the-better (HB). Since the objective of this study is to determine under which conditions CL is better than FL, it is proposed to maximize the HB type *S/N* characterizing the MFT ratio MFT_{FL}/MFT_{CL}. This *S/N* ratio is given by (Ross, 1996; Park, 1998; Montgomery, 2001):

$$\frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$$

where y_i is the *i*th MFT ratio value of the n trial conditions. In fact, every experiment suggested by the OA is run twice and the corresponding *S/N* ratio is computed. Results are shown in Table II.

The ANOVA for *S/N* ratios is carried out. Using pooling technique, the insignificant factors and interactions are pooled up with the error. The initial and pooled ANOVA results are presented in Table III. The analysis results indicate that only the CFs BS, δ and RULE are statistically significant. The factors ST/PT, TT/PT, IAT and OVER are considered insignificant as their *F*-values and contributions are very low. On the other hand, only the interaction RULE × OVER is statistically significant. All the other interactions are insignificant. Figure 4 shows the main effects of the CFs and their interactions and graphically depicts these remarks. In this figure, the importance of the factor is expressed by its slope whereas the importance of an interaction is expressed by the slope difference between the two curves of the interaction.

4.4 Mathematical model development and exploitation

Based on the computed *S/N* ratios, a mathematical model is derived by linear interpolation (Dobson, 2001). In this model, every CF can take one of two values: 1 or 2, depending on the chosen parameter level:

Parameter/interaction	Initial ANOVA SS	DOF	MS	*C*%	*F*		Pooled ANOVA SS	DOF	MS	*F*
ST/PT	5.87	1	5.87	0.51	0.07	Pooled	–	–	–	–
BS	86.65	1	86.65	7.56	1.06		86.65	1	86.65	2.74
TT/PT	29.08	1	29.08	2.54	0.36	Pooled	–	–	–	–
IAT	38.11	1	38.11	3.33	0.47	Pooled	–	–	–	–
OVER	3.40	1	3.40	0.30	0.04	Pooled	–	–	–	–
δ	306.25	1	306.25	26.73	3.75		306.25	1	306.25	9.68
RULE	269.36	1	269.36	23.51	3.30		269.36	1	269.36	8.51
ST/PT × TT/PT	19.92	1	19.92	1.74	0.24	Pooled	–	–	–	–
IAT × RULE	34.24	1	34.24	2.99	0.42	Pooled	–	–	–	–
RULE × OVER	135.21	1	135.21	11.80	1.66		135.21	1	135.21	4.27
BS × TT/PT	7.37	1	7.37	0.64	0.09	Pooled	–	–	–	–
ST/PT × δ	12.49	1	12.49	1.09	0.15	Pooled	–	–	–	–
ST/PT × BS	34.32	1	34.32	3.00	0.42	Pooled	–	–	–	–
Error	163.36	2	81.68				184.80	11	31.65	
Total	1,145.63	15					1,145.63			

Notes: SS, sum of squared deviations; DOF, degree of freedom; MS, mean square; *C*%, percentage contribution; *F*, *F*-value

Table III.
Results of the ANOVA

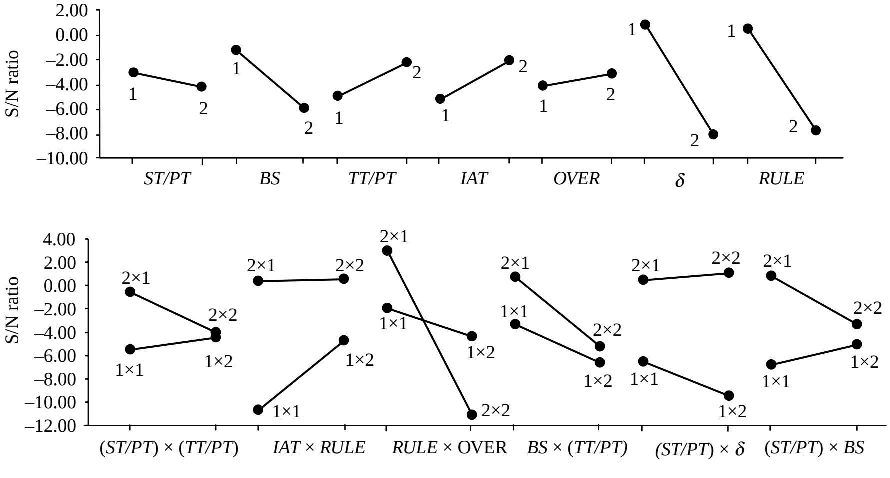


Figure 4.
Parameters effects

$$\frac{S}{N} = 48.95 + 2.00 \times \frac{\mathrm{ST}}{\mathrm{PT}} + 13.46 \times \frac{\mathrm{TT}}{\mathrm{PT}} - 5.69 \times \mathrm{IAT} - 3.45 \times \delta - 16.52 \times \mathrm{OVER} \\ - 9.37 \times \mathrm{BS} \quad - 34.43 \times \mathrm{RULE} - 4.46 \times \frac{\mathrm{ST}}{\mathrm{PT}} \times \frac{\mathrm{TT}}{\mathrm{PT}} + 5.85 \times \mathrm{IAT} \times \mathrm{RULE} \\ + 11.63 \times \mathrm{RULE} \times \mathrm{OVER} \quad - 2.72 \times \mathrm{BS} \times \frac{\mathrm{TT}}{\mathrm{PT}} - 3.53 \times \frac{\mathrm{ST}}{\mathrm{PT}} \times \delta + 5.86 \times \frac{\mathrm{ST}}{\mathrm{PT}} \times \mathrm{BS}$$

A confirmation experiment is carried out to validate the developed model. This experiment consists of adopting the recommended "best" levels of CFs, as shown by Figure 4. The average result from the confirmation test should statistically correspond to the optimum performance estimated by the mathematical model. If the average of the results of the confirmation experiment is within the limits of the confidence interval (CI) of the predicted result, then the mathematical model is considered confirmed; otherwise additional analysis and experimentation are needed (Ross, 1996).

Considering maximum value of *S*/*N* ratio, the optimum levels of the CFs are as follows: ST/PT_1, TT/PT_2, IAT_2, BS_1, δ_1, $OVER_2$, $RULE_1$. In this case, the expected result in terms of *S*/*N* ratio is 9.17 dB. The computed 95 percent CI is equal to $CI = \pm 11.16$ dB. Therefore, the expected result should lie between -2.02 and 20.30 dB. In fact, the "best" expected response of -1.47 dB obtained by the confirmation experiment, which is repeated two times, is within the limits of the CI. The mathematical model is hence considered valid. Consequently, it can be used by the manufacturer to determine the best layout of its MS machines. The manufacturer can also investigate the effect of the change of one or several CFs levels on performances of the two layouts. If the model computed *S*/*N* ratio value is negative then the FL is better than the CL. In contrary, if the predicted *S*/*N* ratio value is positive then the CL outperforms the FL. Finally, the two layouts performances are equivalents if the *S*/*N* ratio value predicted by the mathematical model is close to zero. Table IV depicts the CL and FL superiority contexts expressed as a combination of the CFs.

This table can be used by the manufacturer to determine the more effective layout for every one of the 128 possible CF level combinations. Indeed, the intersection between the line that represents the combination of the ST/PT, TT/PT, BS and OVER levels and the column corresponding to the IAT, RULE and δ levels gives the

Table IV.
Level combinations giving layout superiority

				IAT_1				IAT_2			
				$RULE_1$		$RULE_2$		$RULE_1$		$RULE_2$	
				δ_1	δ_2	δ_1	δ_2	δ_1	δ_2	δ_1	δ_2
ST/PT_1	TT/PT_1	BS_1	$OVER_1$	CL	CL	FL	FL	CL	CL	FL	FL
			$OVER_2$	CL	FL	FL	FL	CL	FL	CL	FL
		BS_2	$OVER_1$	CL	FL	FL	FL	CL	FL	FL	FL
			$OVER_2$	FL	FL	FL	FL	FL	FL	FL	FL
	TT/PT_2	BS_1	$OVER_1$	CL	CL	FL	FL	CL	CL	CL	FL
			$OVER_2$	CL	CL	CL	FL	CL	CL	CL	CL
		BS_2	$OVER_1$	CL	FL	FL	FL	CL	FL	FL	FL
			$OVER_2$	CL and FL	FL	FL	FL	CL	FL	CL	FL
ST/PT_2	TT/PT_1	BS_1	$OVER_1$	CL	FL	FL	FL	CL	FL	FL	FL
			$OVER_2$	CL	FL	FL	FL	CL	FL	CL	FL
		BS_2	$OVER_1$	CL	FL	FL	FL	CL	FL	FL	FL
			$OVER_2$	CL	FL	FL	FL	CL	FL	CL	FL
	TT/PT_2	BS_1	$OVER_1$	CL	FL	FL	FL	CL	FL	FL	FL
			$OVER_2$	CL	FL	FL	FL	CL	FL	CL	FL
		BS_2	$OVER_1$	CL	FL	FL	FL	CL	FL	FL	FL
			$OVER_2$	CL	FL	FL	FL	CL	FL	CL	FL

Notes: X_1, first level of the CF *X*; X_2, second level of the CF *X* outperforming layout. For example, the FL is the best layout for the following CFs levels combination: ST/PT$_2$, TT/PT$_1$, BS$_1$, OVER$_1$, IAT$_2$, RULE$_1$ and δ_2.

The mathematical model can also be used to predict the best layout for "intermediate levels" of the CFs ST/PT, TT/PT, BS, IAT and δ which are continuous factors. Unlike these CFs, OVER and RULE are discrete and can be investigated only for the two levels 1 and 2. For example, for the following setting combination: ST/PT$_{1.2}$, TT/PT$_{1.1}$, BS$_{1.3}$, OVER$_1$, IAT$_{1.6}$, RULE$_2$ and $\delta_{0.65}$ the FL outperforms the CL.

5. Conclusion

This paper presents an objective comparison methodology between functional and CLs. The main goal of this methodology is to help MS managers choosing the most appropriate layout to their manufacturing context. The developed methodology integrates discrete event simulation and the TM for the design of experiments and results analysis. Through a minimal experimental effort, this method permits to reliably evaluate the effect of each MS parameter on the system performance and to reveal the possible interactions between these parameters. The main outcome of the proposed methodology is a mathematical model depicting the superiority trend of the two layouts. In fact, once developed and validated, the mathematical model can be used by the MS manager to predict the *S*/*N* ratios for any combination of the MS parameters within the scope of the experimental study. For every parameter combination, the sign of the *S*/*N* ratio indicates the best layout. The model can also be exploited to interpolate the results between the studied levels of continuous parameters such as batch inter arrival time or batch size. The application of this methodology on an illustrative example showed the efficiency of this methodology for the choice of the best layout for an MS.

Many aspects of the comparison methodology are currently being developed. The first task is the refinement of the performed study by considering three levels for each CF in order to capture non-linearity. Then, the enlargement of the application scope to other domains is also projected. This should increase the chance of the proposed methodology to be successfully applied and validated on real cases.

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