Operations Management Research and Cellular Manufacturing Systems:

Innovative Methods and Approaches

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Chapter 9

Cellular or Functional Layout?

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ABSTRACT

The cellular layout has been compared to the traditional functional layout using multiple comparison methodologies that either lack objectivity or are highly time-consuming. The main purpose of this chapter is to propose a novel and objective methodology. Hence, a critical analysis of ten comparison studies is followed by the presentation of the layouts simulation models. Subsequently, the proposed comparison methodology is described. Following this methodology, simulations are conducted according to a plan of experiments developed from Taguchi standard orthogonal arrays. Consequently, results, expressed in Signal to Noise ratios, are analyzed using ANOVA. Next, a mathematical model is derived by interpolation between the factors and interactions effects. This model must be validated by the confirmation test, otherwise the comparison methodology should be reiterated while considering new interactions. This cycle should be reiterated as much as necessary to obtain a valid mathematical model. The proposed comparison methodology has been applied with success on an academic manufacturing system.

INTRODUCTION

The increased competition within industry has resulted in manufacturing companies spending considerable effort to improve flexibility and responsiveness to meet customer needs. Cellular manufacturing, a facet of group technology, has emerged as one of the major techniques being used for the improvement of manufacturing competitiveness. A large number of empirical, analytical and simulation studies have been devoted to compare the cellular layout (CL) to the classical functional layout (FL). Simulation-based comparative studies constitute the mainstream of this research field. Varied results were reported by these comparative simulation studies. Indeed, different researches found the FL always superior to the CL with regard to all used performance measures (Jensen,

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Malhotra, & Philipoom, 1996; Morris & Tersine, 1990, 1994). Further researches reported that the CL is superior to the FL in all operating conditions (Pitchuka, Adil, & Ananthakumar, 2006; Shafer & Charnes, 1992). Finally, other simulation studies showed that every layout could outperform the other in different particular experimental conditions (Faizul huq, Douglas, & Zubair, 2001; Farrington & Nazametz, 1998; Li, 2003; Shafer & Charnes, 1995; Suresh & Meredith, 1994). The divergence in the studies conclusions is referred to as the "cellular manufacturing paradox" (Shambu, Suresh, & Pegels, 1996). In fact, Agarwal and Sarkis (1998) and Shambu et al. (1996) reviewed a number of FL-CL comparative studies. However they did not identify any objectivity flaws responsible for the conflicting conclusions. Indeed, they simply reported the major findings of some published studies without any critical objectivity assessment.

Actually, methodologies used by comparison studies vary widely but can be classified into three groups. In the first group, authors used the one-factor-at-a-time method. So the two layouts are first compared for one manufacturing context considered as the "base model". Then, other experiments are carried out in order to test the robustness of the layout choice obtained in the base model. Every experiment corresponds to the modification of a single operating factor (Morris & Tersine, 1990, 1994). In the second group authors considered only some specific combinations of the studied factors settings without any justification (Faizul huq et al., 2001; Li, 2003; Suresh & Meredith, 1994). In the third group authors used the full factorial design technique in order to study the effect of all factors (Farrington & Nazemetz, 1998; Jensen et al., 1996; Pitchuka et al., 2006; Shafer & Charnes 1992, 1995). Methodologies belonging to the two first groups undoubtedly lack objectivity in the choice of the experimentation conditions. Therefore, they do not permit to attach any statistical confidence level to their conclusions. In addition, they do not provide any information about factor interaction. The third group methodology is highly time-consuming. In addition, it is impractical when the number of factors to study is large.

This chapter essentially focuses on the development of an objective FL-CL comparison. It first highlights the lacks of objectivity of the main published FL-CL simulation-based comparison studies in order to explain the origin of their conflicting conclusions. Then it deals with the development of comprehensive FL and CL simulation models using the widely used commercial simulation software Arena 7.0. Finally, it presents the framework of a methodology, based on the coupling of the Taguchi method of experiment design (TM) and simulation. This methodology can be easily applied to any manufacturing context and provides trustworthy results with a minimum experimentation effort.

The remainder of this chapter is organized as follows. The next section presents a taxonomy of the key factors used in the main published FL-CL comparison simulation studies. The foremost used performance measures are also presented in this section. Finally it presents and analyses the findings of a number of relevant studies. The third section presents some general simulation features, needed for modeling both layouts. Then, it respectively gives details of the developed FL and the CL simulation models. Section four gives a general presentation of the objective comparison methodology and then presents a comprehensive academic case study depicting its application. The final section includes some general conclusions and discusses future work prospects.

COMPARATIVE STUDIES FRAMEWORK

Main Experimental Factors

General Manufacturing System (MS) Characteristics

Every MS is characterized by a number of machines arranged either into departments in the functional layout, or else, into manufacturing cells in the cellular layout. Following the FL structure, the shop is composed of *d* departments *Di* (*i*=1, …, *d*). Each of them includes *Mn* functionally equivalent machines. In contrast, the CL is composed of *c* independent manufacturing cells *Cj* (*j*=1, …, *c*). Each cell is a cluster of *Mf* different machines dedicated to a number of similar part types. Furthermore, every MS is designed for a demand pattern comprising different products. Products are identified by two indicators, which are the type (*t*) and the family (*f*). Products are grouped into families according to the similarity of their manufacturing process. Each product type requires a number of manufacturing operations (*mopt*).

Degree of Decomposability of the Part Machine Matrix (DD)

This degree translates the feasibility of the decomposition of the MS into independent cells. In fact, the more the product/machine matrix is diagonal, the more the decomposability is feasible. This degree is negatively correlated to the density of off-diagonal elements.

Batch Size (BS)

Products are generally manufactured and transferred in batches in order to reduce machine setup and transport between machines. Numerous authors included *BS* in there comparison studies as a variable factor and demonstrated that the combination of small batch sizes with an efficient scheduling rule results in the improvement of the cellular layout performances. Most authors used the same batch size for both cellular and functional layouts.

Demand Rate (DEMAND)

The demand rate is mainly expressed by the batch inter-arrival times (*IAT*) in the MS. A large part of authors generated this time by common probabilistic distributions. Others used constant *IAT*. Besides, some authors focus only on the stability of this factor without changing its average value.

Transfer Time (TT)

This parameter corresponds to the interdepartmental travel times in the FL. They are often modeled using appropriate probabilistic laws. In the CL these times correspond to the durations of intra-cell moves. Generally, they are very small compared to those in the FL.

Transfer Mode (TM)

Because of the considerable interdepartmental distances in the FL products are generally transferred by batches in order to reduce transfer costs. Some studies also used this transfer mode between same-cell machines whereas others make use of operations overlapping. This mode exploits the proximity of same- cell machines to allow simultaneous execution of different operations on parts of the same batch.

Flow Direction (FLOW)

A number of authors included the flow direction within a cell as an experimental factor. This factor has two possible levels: “unidirectional” or “backtracking allowed”.

Scheduling Rules (RULE)

Part batches arriving at a department or a cell are put in a waiting queue until the required machine becomes idle. These batches are then sequenced in order to establish the order in which they will be processed. This order is specified by the use of standard scheduling rule such as “First Come First Served” (FCFS), “Shortest Process Time” (SPT), “Earliest Due Date” (EDD) or else, “Repetitive Lots” (RL). The limited versions of the first three rules, FCFS-L, SPT-L and EDD-L are used in order to avoid the duplication of machines setups for the same product type. Finally, the RL rule selects batches of the same type that the one just processed in order to minimize setups.

Processing Time (PT) and Set up Time (ST)

As for the *IAT*, most studies generally modeled both times by independent probabilistic laws. On the other hand, other studies formulated *ST* as a fraction of *PT*.

Set up Time Reduction Factor (δ)

This factor materializes one of the most key advantages of the CL. Indeed, part types of a same family need generally similar setups. Hence, if a machine is set up for a part type and then should be set for a same-family part type, the nominal setup time for the second part is reduced by the δ factor.

Performance Measures

Work in Process (WIP)

WIP is one of the most popular performance measures used in the FL-CL comparative studies (Farrington & Nazametz, 1998; Jensen et al., 1996; Li, 2003; Morris & Tersine, 1990, 1994; Shafer & Charnes, 1992, 1995; Suresh & Meredith, 1994). It essentially characterizes the fluidity of the material flow in the system.

Mean Flow Time (MFT)

MFT constitutes the other most popular measure used in FL-CL comparative studies (Faizul huq et al., 2001; Farrington & Nazametz, 1998; Jensen et al., 1996; Li, 2003; Morris & Tersine, 1990; Shafer & Charnes, 1992, 1995; Suresh & Meredith, 1994). It also characterizes the fluidity of the material flow in the system. The *MFT* is the average time that every batch remains in the system in order to be manufactured.

Due Date Related Measures

Researchers used essentially Mean Tardiness (*MT*) and Mean Earliness (*ME*) as due date related performance measures (Farrington & Nazametz, 1998; Jensen et al., 1996). *MT* is the average over all tardy jobs of the difference between delivery date and the promised due date. *ME* is similarly obtained for all early jobs. Other researchers used the percentage of tardy jobs (*TARDY*) and the percentage of early jobs (*EARLY*).

Other Measures

FL-CL comparative studies consider several other performance measures. The system *Throughput*, considered as productivity measure, is the average number of parts exiting the system by time unit (Faizul huq et al., 2001; Morris & Tersine, 1994). It is also used for detecting the attainment of steady state indicator in a simulation run. Besides, some studies used the operator utilization rate (*OPUR*) (Morris & Tersine, 1994), the average machine utilization rate (*MUR*) (Farrington & Nazametz, 1998; Morris & Tersine, 1994; Shafer, & Charnes, 1995), the mean "queue" waiting time (Pitchuka et al., 2006) or the average *ST/PT* ratio (Li, 2003) as performance indicators. The first two measures must be maximized to ensure a high degree of resource exploitation but the third and fourth measures should be minimized to improve the efficiency of the MS.

Comparative Studies Findings

By means of four simulation experiments, Morris and Tersine (1990) examined the influence of the ratio *ST/PT, TT*, *DEMAND* stability and parts *FLOW* within cells on the performance of CLs compared to FLs. In this comparative study, the performances were measured using *MFT* and *WIP*. Results demonstrate that in the quasi totality of the tested contexts, the FL always outperforms the CL and generates smaller *MFT* and *WIP*. Besides, comparison results reveal that the ideal context for CL must be characterized by a high *ST*/*PT* ratio, a stable *DEMAND*, a unidirectional *FLOW* and a substantial *TT* between process departments.

To find out the operating conditions under which the CL outperform the FL, Shafer and Charnes (1992) investigated 24 combinations of *DD*, *mopt*, *PT* and *BS*. As for the previous study, authors used the same performance measures. They found the CL superior to the FL in all operating conditions according to both performance measures.

Morris and Tersine (1994) extended the results of their first comparison study (Morris & Tersine, 1990) by investigating the impact of a dual resource constrained shop on the performances of CL and FL using three operator scheduling rules in the CL. Simulation observations were collected for four performance measures including the mean *Throughput*, the *WIP*, the *MUR* and the *OPUR*. Results reveal that the FL outperformed the CL on all of the used performance measures regardless of the operator scheduling rule.

Authors investigate the sensitivity of their results relatively to changes in shop congestion level and changed respectively the *IAT* and *OPUR* in two other experiments. It appeared that the FL still outperforms the CL.

Besides, Suresh and Meredith (1994) aimed to overcome the loss of pooling synergy in the CL. Hence, they used simulation in order to compare the CL to an efficiently operated FL (EFL) using average *MUR*, *WIP* and *MFT* to assess the two layout's performance measures. The EFL is characterized by an optimal *BS*, a reduced *TT* and part-family-oriented scheduling rules. The main experimental factors involved in this study were *PT*, *ST*, *BS*, δ and *IAT*. First, every experimental factor was tested separately. Then all the experimental factors were tested together. The FL was found to be superior to the CL for large batch sizes (*BS*>32). However, for relatively small *BS*, the CL could outperform the FL if δ is smaller than 0.2. Comparison results do not change when the variability of *PT*, *ST* or *IAT* were separately reduced. On the other hand, if all factor effects were combined, the CL outperformed the FL even for small *BS*.

Shafer and Charnes (1995) used simulation to study a manufacturing context inspired from Morris and Tersine (1990). In fact, they used the same levels of the following factors: *t*, *f*, *c*, *d*, *Mn*, *Mf* and *mopt*. Authors aimed to compare alternative loading procedures for CL and FL in a variety of operating environments defined by combinations of 4 factors: *FLOW*, *TT,* labor constraints and MS congestion level. The third factor was modeled using two levels of the operator number while the last factor was modeled through the variation of the *PT*. Besides, each layout was investigated using two loading policies. For the FL the first policy permitted machine dedication while the second did not. On the other hand, for CL the first policy restricted the processing to only one batch at a time in a cell and the second allowed the processing of different batches at the same time. Both policies authorized CL operations overlapping. The authors used *MFT* and *WIP* in a two stage comparison methodology. In the first stage, labor constraints were not considered. 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 during setups and processing operations. The first stage simulation results demonstrate that the two layouts were equivalent regarding *WIP* while the CL generated lower *MFT* than the FL. In contrast, in the second comparison stage the FL showed lower *MFT* than the CL. The authors justified this result by the labor constraint effect on the CL. Indeed, according to the authors the labor constraints handicaps more seriously the CL since it reduces the operations overlapping possibilities while its effect on the

FL is not significant since the departments have only 3 machines in average.

Another study by Jensen et al. (1996) assessed the FL and CL performances through *MFT*, *WIP MT*, *ME* and *TARDY*. They based their study on a full- factorial experimental plan involving layout type, *RULE*, *DEMAND* variability and δ as experimental factors. To determine the influence of each factor on the studied performance measures, the authors analyzed their simulation results by ANOVA. Aside from the layout type, the most influent factor was found to be *DEMAND* variability followed by δ and *RULE*. Then, the authors performed a pairwise comparison of *RULE*. Results demonstrate that SPT-L and EDD were the best performing rules regarding *MFT* and *MT* respectively. Finally, they compared layouts using the best found *RULE*. The results of this final step revealed that the FL was always superior to the CL with regard to all performance measures.

As for Farrington and Nazemetz (1998), their comparative study is based on a three-factor-full-factorial experimental plan. The three experimental factors were the layout type, the *PT* variability and the *IAT* variability. It's worth noting here that the high variability level was associated to a small *BS* and vice versa. They assessed the two layouts using different performance measures, namely *MFT*, *WIP*, *TARDY*, *MUR* and a number of others less common measures. Comparison results prove that the FL is superior to the CL in a context defined by a high variability of *PT* and a low variability of *IAT*. 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.

Faizul huq et al. (2001) presented in their comparison study a straightforward two-factor-full-factorial simulation plan using the *MFT* and the *Throughput*. The two studied factors were *BS* andδ. For the sake of objectivity, the authors used the EFL concept. ANOVA investigation showed that the two layout *Throughput* performances were not significantly different. In deed, the two layouts presented significant differences in some of the studied combinations only in terms of *MFT*. In fact, The CL outperformed the FL only for small *BS* and very largeδ. In all other conditions, the FL was clearly superior.

Regarding Li (2003), the author used *MFT* and *WIP* to explore the superiority domains of both layouts in a diversity of contexts. These contexts are defined by the *FLOW*, the *TM*, the variability of *PT*, the variability of *ST* and finallyδ. The performance measures results analysis showed that the major factor in establishing the superiority of one of the two layouts isδ. Hence, the CL outperformed the FL at high level of δ and the FL was the best layout in the low δ region. Both layouts showed equivalent performance measures for intermediate value ofδ.

The last reviewed study, done by Pitchuka et al. (2006), compared FL to CL using a four-factor-full-factorial experimental plan featuring *PT*, *ST*, *BS* and *IAT*. The authors considered only the "queue" waiting time as performance measure. It was shown that the CL can outperform the FL in the majority of the studied contexts. Indeed, in the CL numerous work centers generated inferior "queue" times to those of the corresponding work centers in the FL.

Objectivity Assessment

Conditions Favoring FL

Jensen et al. (1996), Pitchuka et al. (2006) and Shafer and Charnes (1992) considered very low *TT* which implicitly advantage the FL, since one of the main advantages of the CL is time saving by locating machines required to manufacture a part close to each other. On the other hand, Jensen et al. (1996), Morris and Tersine, (1990, 1994) and Pitchuka et al. (2006) used a CL with no operations overlapping allowed in part processing. This does not permit to take advantage of CL benefits. Moreover, Farrington and Nazametz (1998) stated that they 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 main advantages of the CL.

Conditions Favoring CL

The study of Shafer and Charnes (1992) is obviously biased in favor of the CL. In deed, the authors consider single-machine departments. So, they eliminate the main and probably the only benefit of this type of layout: the pooling synergy effect between same department machines. Consequently, the results were clearly in favor of the CL even with the assumption of null transfer times advantaging the FL. Regarding Li (2003), the study featured unidirectional cell *FLOW* by duplicating the necessary machines to avoid backtracking. This indirectly led to the reduction of the cell number. The machine duplication within cells biased the comparison results in favor of the CL. In fact, this attaches to the CL the main advantages of the FL which is the synergy between functionally equivalent machines. As for Suresh and Meredith (1994), they used FL *TT* relatively very high compared to the *PT*. This probably advantage the CL and make clear why its performance are superior to the performance of the FL in almost all the testing contexts even though no operations overlapping has been used in the CL.

Other Conditions

This category essentially includes the lack of vital information about the used experimental factor settings as well as key elements defining the manufacturing contexts. Indeed, even if Morris and Tersine, (1990, 1994) provided in their studies the material handling equipment speed, they did not mention any distances between departments or machines. These distances are required in order to evaluate the *TT* in the two layouts. On the other hand, Farrington and Nazametz (1998) and Shafer and Charnes (1992) did not mention the *RULE* they used. In addition, Farrington and Nazametz (1998) failed to report numerous key experimental factors such as *mopt*, *IAT* and *PT*. Despite its established importance, Jensen et al. (1996) did not use the *BS* as an experimental factor neither did they mention its constant value used throughout the investigation.

Other lacks of important data are included in this category, particularly technical simulation-related information such as the replication length (Farrington & Nazametz, 1998; Li, 2003) and the warm-up period length (Farrington & Nazametz, 1998). On the other hand, numerous incongruities appear in different comparative studies. For example, the difference between the two shop configurations of the CL studied by Li (2003) is not clear. Indeed, in the figures illustrated by the authors, the arrows indicating the products *FLOW* show that there is no backtracking flow even in the CL with backtracking flow allowed. These incongruities are more serious in Faizul huq et al. (2001) study. Indeed, despite stating that no inter-cell moves were allowed, the authors defined the inter-cell travel time by a uniform law.

The use of inappropriate MS data appears especially in the study of Faizul huq and al. (2001). Indeed, the major flaw of this study 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 factor δ becomes irrelevant and any results showing the importance of this factor are seriously questionable.

SIMULATION MODELS

Basic Simulation Features

FL and CL layouts simulation models are developed using the commercial simulation software

Arena 7.0 (Kelton, Sadowski, & Sadowski, 2002). This simulation tool integrates all the needed simulation functions including animation, analysis of input and output data. Every MS model consists of the four main components: manufacturing orders launching and attribute assignation, part transfer, part manufacturing and statistics collection.

Manufacturing Orders Launching and Attribute Assignation

Manufacturing orders (MOs), being batches of parts of the same type, are launched by "Create" modules. Every "Create" module defines batches *IAT* following the used probabilistic rule in addition to their *BS*. A specific "Create" module is dedicated for each part type. As soon as parts are lunched, they pass through an "Assign" module where characteristics are attributed to them. These characteristics are either time-related such as *PT* and *ST*, or also identification indicators such as part's type as well as part's family and factors necessary to the MS piloting like part's routing or "Sequence".

Part Transfer

Parts are transferred, either individually or in batches, between physical locations modeled by the "Station" modules, in which they should undergo the required manufacturing steps. These locations are either machines in CL or departments in FL. Transfer are carried out by "Route" modules permitting to prescribe destinations as well as transfer times. These modules use "Sequence" attribute of the transferred parts in order to prescribe the next destination. The "Sequence" corresponds to the part routing expressed as stations list.

Two manufacturing strategies could be followed for the parts transfer in the shops: "with operations overlapping" or "without operations overlapping". In the first strategy, parts of the same batch could be processed simultaneously on different machines of a department or a cell. In the second strategy, all parts of the same batch are processed on the same machine of the cell or department before being transferred collectively to the next machine or department. In all cases, batches must be split by "Separate" modules before accessing any machine. Batch reconstitution for transfer is performed using "Batch" modules.

Part Manufacturing

Every machine is modeled by a "Process" module, associated to a "Station" module and a "Resource" module. The "station" module determines the physical location of the machine and the "Resource" module represents the capacity and the availability of the machine itself. In fact, the "Process" module seizes the associated resource for the required period of time and then releases it. So, the machine becomes idle and available again for manufacturing another part. The machine resource is seized during a period of time that corresponds to the *PT* of the part being processed and eventually the required *ST* if the machine was set for a different part type. The *ST*, when relevant, is weighed by the setup reduction factor δ whenever the part type belongs to the family of the last processed one.

Statistics Collection

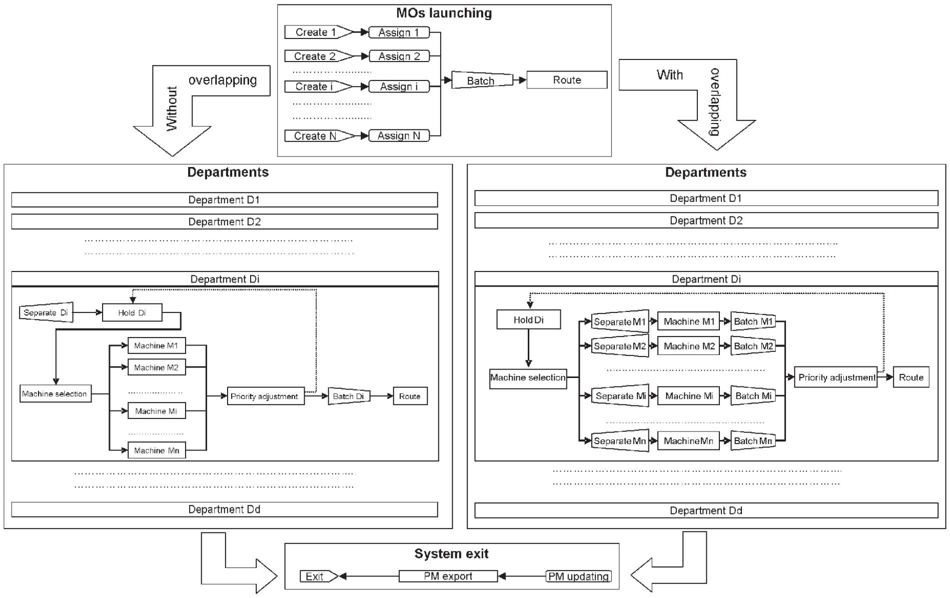
Before leaving the MS, every batch must go through an "Assign" module in which the parameters defined as performance measures are computed and updated. The acquired data is then stored in an Excel file using a "Readwrite" module for eventual treatment and analysis.

Functional Layout Model

The functional layout model is composed of three sections: "MOs launching", "Departments" and "System exit" (see Figure 1).

MOs are launched by "Create" modules dedicated each part type. Each "Create" module

Figure 1. FL model



is coupled to an "Assign" module. The generated parts are then grouped into batches and routed to their first manufacturing step's department. A batch arriving at a department is made waiting in a queue modeled by a "Hold" module. This module is governed by a priority rule that could be FCFS, SPT or any other priority rule. When at least one of the department machines becomes available, the "Hold" module releases the prioritized batch from the waiting queue. The released batch is then transferred to the "Machine selection" sub-model that selects one among the available machines. The logic of this sub-model is coherent with the waiting queue priority rule.

When operations overlapping are not allowed, every batch is split once it reaches the assigned machine. Hence, each batch can be treated only by a single machine. On the other hand, if operations overlapping are permitted, parts batches are split before accessing the department queue. So, parts become independent and could be dispatched to several machines of the same department to be processed simultaneously. In both cases, batches are gathered by a "Batch" module right after processing and before the transfer to next manufacturing step. The combination of the operations overlapping strategy, the machine selection process and the waiting queue priority rule define the shop scheduling policy.

Cellular Layout Model

The CL model is composed of "*c*" sub-models corresponding to the "*c*" MS cells. Each sub-model is composed of three sections: "MOs launching", "Machine cells" and "Cell exit".

As for the FL, MOs are launched by "Create" and "Assign" modules dedicated to each part type. The generated parts are then grouped in batches before being routed to the general cell queue. Such a queue holds part batches until their first routing step machine becomes available. In addition, each machine has its own waiting queue. Both queues are governed by the same priority rule.

If operations overlapping are allowed, batches are split just before leaving the cell general queue. Hence, every part can follow its routing without waiting for the other batch parts. Batches are finally regrouped just before the cell exit. In contrast, if operations overlapping are not implemented, every batch is split when it reaches the machine next machine on its routing. Batches are regrouped once their processing is accomplished. Then, they are transferred towards the following machine or to the system exit.

THE OBJECTIVE COMPARISON METHODOLOGY

Overview

The objective comparison methodology (OCM) aims essentially at the development of a mathematical model permitting to predict the superiority of one layout or the other. It is the product of the application of Taguchi method of experiment design. Hence, the OCM is mainly composed of 3 main phases:

- Phase 1: Choosing MS parameters and setting their levels
- Phase 2: Construction of the experiments plan, results analysis and development of the mathematical model
- Phase 3: Refinement of the simulation plan and improvement of the mathematical model

Each of these phases is composed of one or several stages. Some stages should be reiterated several times.

Phase 1: Choosing Levels of the Manufacturing System Parameters

In the first phase of the OCM the manager must choose the MS parameters as well as their levels. Generally, every MS can be characterized by three types of parameters: signal factors, control factors and noise factors.

Figure 2. CL model

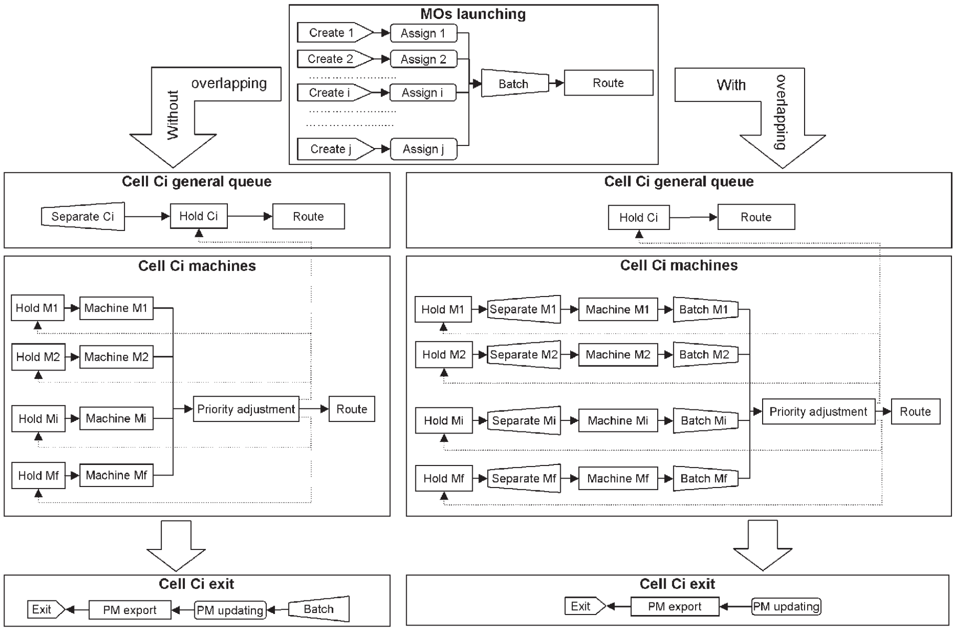
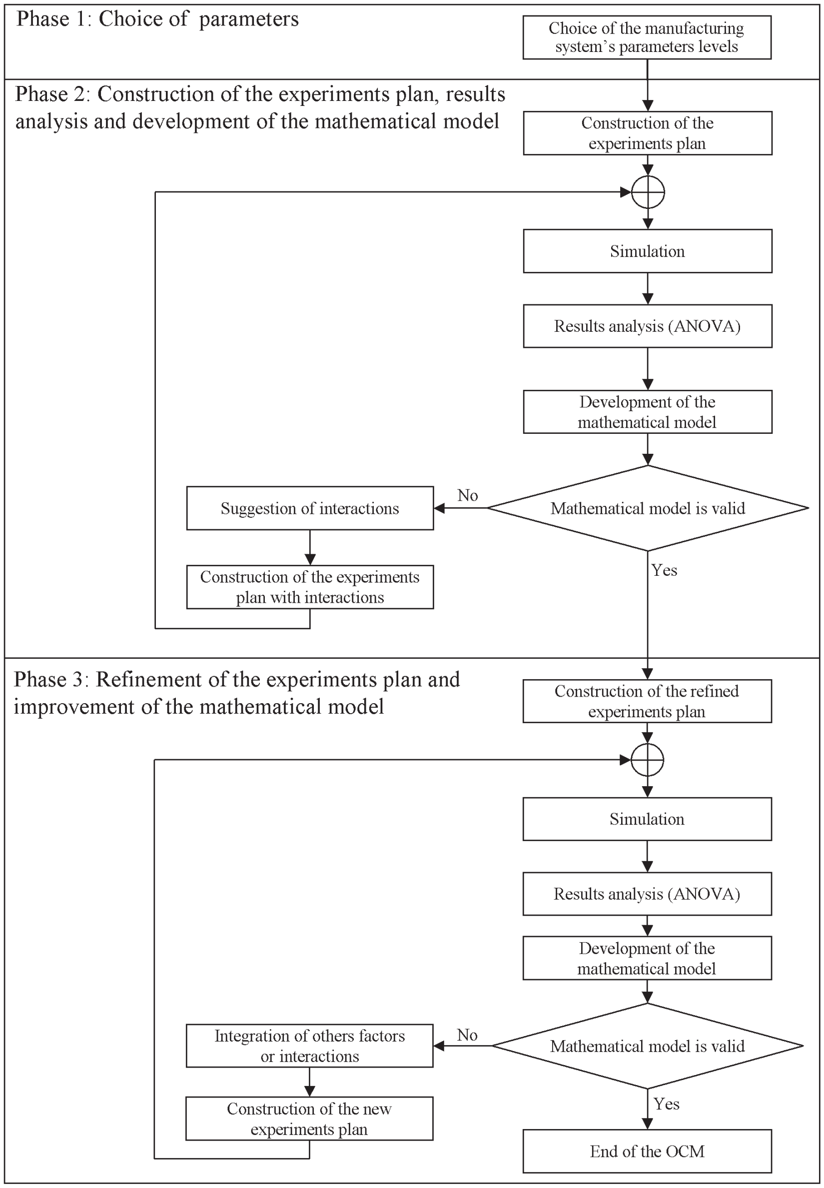


Figure 3. Overview of the OCM



Signal Factors (SF)

Signal factors are factors that are expected to affect the average response. In addition, these factors identify the manufacturing context and are kept constant in every application of the OCM. This category includes the department's number *d*, the cell's number *c*, the number of equivalent machines in every department *Mn* and the number of different machines in every cell *Mf*. The four other signal factors are the number of part families *f*, the number of part types by family *t*, the number of manufacturing operations *mopt* and the existence or no of inter-cell moves.

Control Factors (CF)

As for the signal factors, control factors can affect the average response but, more importantly, can affect the extent of the variability about the average response. These factors are to be varied throughout the simulation plan. This category includes the *ST,* the *PT*, the *TT,* the I*AT* and theδ. The three other Control factors are the *BS*, the *RULE* and the *TM*. For more objectivity of comparison results, *ST*, *TT* and *PT* are put into the following ratio forms *ST/PT* and *TT/PT*. Indeed, *ST* and *TT* being nonproductive activities, these ratios are used to compare them to *PT* which is a productive activity. In addition to the studied CFs, several factor interactions (CFI) could also be investigated in every application of the OCM. CFI between CF_x and CF_y is here noted $CF_x x CF_y$.

Noise Factors (NF)

Noise factors are difficult or even impossible to control. Some of these factors could have a direct influence on the MS performances. Hence, instead of controlling them, the methodology aims at determining a solution in terms of CF that is robust relatively to unpredictable variations of *NF*.

Phase 2: Construction of the Experiments Plan, Results Analysis and Development of the Mathematical Model

The main purpose of the second phase of the OCM is to develop the mathematical model. This model gives an interpretation of the SM parameters effect's on the performances of the two layouts. It is developed through the following stages:

- Stage 1: An initial plan of experiments is constructed using standard OAs developed by Taguchi (Taguchi, Elsayed, & Hsiang, 1989). This plan is a set of experiments (simulations) where several CFs levels are varied from an experiment to another. It permits to considerably minimize the experimental effort.
- Stage 2: Simulations are conducted and performance measures of the two layouts are collected. The performance measures are expressed 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). There are three type of *S/N* ratios: lower-the-better (LB), nominal-the-best (NB), and higher-the-better (HB). In the OCM, the HB type *S/N* is used.
- L is better than FL, it is proposed to maximize the HB type S/N characterizing the MFT ratio MFTFL/MFTCL
- Stage 3: Simulations results are then analyzed by the analysis of variance method (ANOVA). The ANOVA establishes the relative significance of CFs in terms of their percentage contribution to the response (Phadke, 1989; Ross, 1996). The relative significance of CFs is translated by the Fischer factor "*F*" (Montgomery, 2001). The ANOVA also estimates the variance of error.
- Stage 4: The mathematical model is developed by interpolating the CFs effects. The validity of the developed mathematical model is then verified through the confirmation experiment. This experiment consists of adopting in an extra simulation experiment the best levels of CFs. 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 (Kiefer, 1977). Hence the OCM can move to the following phase. Otherwise, interactions between CFs are taken in account in a new model. The second phase of the OCM is then reiterated from the third stage. This cycle should be reiterated

as much as necessary to get a valid mathematical model. In each iteration, the insignificant interactions must be eliminated and replaced by other interactions.

Phase 3: Refinement of the Simulation Plan and Improvement of the Mathematical Model

The purpose of this phase is to refine the simulation plan and to improve the mathematical model developed in the second phase. So, in this plan, only the most significant CFs and CFIs are considered. Besides, for each CF, additional levels are investigated to study the non-linearity effect of the process factors. This phase is very similar to the second phase. Indeed, it essentially includes the same main stages. Only the choice of factors and interactions to integrate in the mathematical model is different. Once the improved mathematical model developed, its validity is tested.

Academic Case Study

The studied MS is inspired from the comparison study of Morris and Tersine (1990). This MS is composed by 30 machines grouped in 8 departments in the FL and 5 cells in the CL. It is also characterized by 30 part types grouped in 5 families. Every part family is composed of 6 part types. Each part type requires from 2 to 6 production operations. In addition, no inter-cell moves are required.

The FL and CL simulation models were developed using the ARENA commercial software. Observations were then collected for two performance measures: *MFT* and *Throughput*. The second measure is used solely for warm up period detection. The results show that a warm up period of 200000 minutes is needed. The models can then be run for 800000 minutes.

Choice of MS Parameters

The CFs are here studied using two levels each as depicted in Table I. It is worth noting that the original level corresponds to the level initially used in the MS.

Initial plan of Experiments

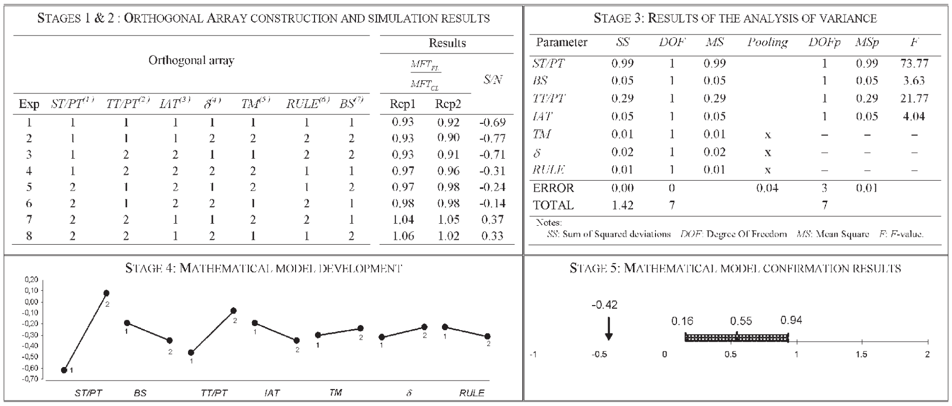
Each of the two level CFs has 1 degree of freedom (DOF). Hence, the total degree of freedom (TDOF) required for the studied seven CFs is 8 [=7×1+1]. As per Taguchi's method the total experiments number of the selected OA must be greater than or equal to the TDOF, an $L_8(2^7)$ OA was selected for the initial experiments plan (Taguchi et al., 1989). This OA has seven columns and eight experiment-runs (rows). The seven CFs are assigned to the OA columns as depicted in Figure 4 (stages1&2). Every suggested experiment by the OA is then run for 2 replications in order to compute the *S/N* ratios. Results are shown in Figure 4 (stages 1&2). The results of ANOVA indicate that only the CFs *ST/PT*, *TT/PT*, *BS* and *IAT* are statistically significant (Figure 4-stage 3). Figure 4 (stage4), that depicts the main effects of the CFs, confirms these remarks. In this figure, the importance of the CF is expressed by its slope.

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

$$
\begin{aligned}
S / N = {} & \text{-}1.53 + 0.70 \times (ST / PT) \text{ - } 0.16 \times BS + 0.38 \\
& \times (TT / PT) \text{ - } 0.16 \times IAT + 0.07 \times TM + 0.09 \\
& \times \delta \text{ - } 0.08 \times RULE
\end{aligned}
\tag{1}
$$

Then, the confirmation experiment considers the maximum value of *S/N* ratio to choose optimum levels of the CFs. Hence the chosen levels are ST/PT_2, TT/PT_2, IAT_1, BS_1, δ_2, TM_2 and $RULE_1$ where X_i is the i^th level of the control factor *X*.

Figure 4. OCM application: Initial experiments plan



STAGES 1 & 2 : ORTHOGONAL ARRAY CONSTRUCTION AND SIMULATION RESULTS

Orthogonal array								Results		
								MFT_{FL}/MFT_{CL}		S/N
Exp	ST/PT$^{(1)}$	TT/PT$^{(2)}$	IAT$^{(3)}$	$\delta^{(4)}$	TM$^{(5)}$	RULE$^{(6)}$	BS$^{(7)}$	Rep1	Rep2	
1	1	1	1	1	1	1	1	0.93	0.92	-0.69
2	1	1	1	2	2	2	2	0.93	0.90	-0.77
3	1	2	2	1	1	2	2	0.93	0.91	-0.71
4	1	2	2	2	2	1	1	0.97	0.96	-0.31
5	2	1	2	1	2	1	2	0.97	0.98	-0.24
6	2	1	2	2	1	2	1	0.98	0.98	-0.14
7	2	2	1	1	2	2	1	1.04	1.05	0.37
8	2	2	1	2	1	1	2	1.06	1.02	0.33

STAGE 3: RESULTS OF THE ANALYSIS OF VARIANCE

Parameter	SS	DOF	MS	Pooling	DOFp	MSp	F
ST/PT	0.99	1	0.99		1	0.99	73.77
BS	0.05	1	0.05		1	0.05	3.63
TT/PT	0.29	1	0.29		1	0.29	21.77
IAT	0.05	1	0.05		1	0.05	4.04
TM	0.01	1	0.01	x	–	–	–
δ	0.02	1	0.02	x	–	–	–
RULE	0.01	1	0.01	x	–	–	–
ERROR	0.00	0		0.04	3	0.01	
TOTAL	1.42	7			7		

Notes:
SS: Sum of Squared deviations DOF: Degree Of Freedom MS: Mean Square F: F-value.

STAGE 4: MATHEMATICAL MODEL DEVELOPMENT

STAGE 5: MATHEMATICAL MODEL CONFIRMATION RESULTS

In this case, the expected result in terms of *S/N* ratio is 0.55 Db. The computed 95% confidence interval is equal to CI = ±0.39 Db. Therefore, the expected result should lie between 0.16 Db and 0.94 Db. As depicted in Figure 4 (stage5) the best expected response of -0.42 Db obtained by the confirmation experiment is outside the limits of the CI. The mathematical model is hence considered invalid. Additional analysis and experimentation are needed.

Simulation Plan with Interactions

Two additional iterations were needed to obtain a valid mathematical model. Only the results of the second iteration are depicted here. Based on the first iteration simulation plan ANOVA results, the simulation plan in the second iteration considers *TT/PT×RULE*, *ST/PT×RULE*, *ST/PT×BS*, *BS×RULE, TT/PT×BS, IAT×RULE* and *IAT×BS* as CFIs. Each of these CFIs has 1 DOF. The required TDOF is then equal to14 [=7×1+6×1+1]. Hence, the $L_{16}(2^{15})$ is the OA to use. This OA has fifteen columns and sixteen experiment-runs. The factors were assigned to the $L_{16}(2^{15})$ OA using the linear graphs displayed in the Figure 5 (stages1&2). This figure also shows the associated simulation results.

ANOVA results indicate that only the CFs *BS*, *ST/PT, IAT* and δ are statistically significant (Figure 5- stage 3). It also demonstrates that only the CFIs *TT/PT×RULE, TT/PT×BS* and *ST/PT×BS* are statistically significant. Figure 5 (stage4) illustrates the main effects of the CFs and CFIs. In this figure the importance of a CFI is expressed by the slope difference between the interaction two curves. The mathematical model is then developed:

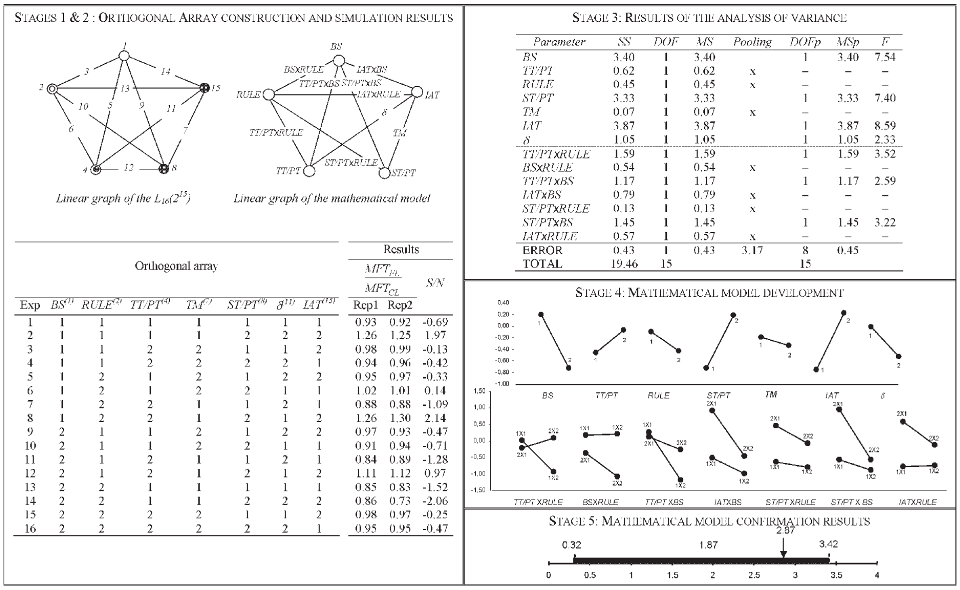
$$\begin{aligned} S/N = {} & \text{-}4.44 + 1.70 \times BS \text{ - } 3.12 \times (TT/PT) + 0.54 \times RULE \\ & + 3.26 \times (ST/PT) \text{ - } 0.14 \times TM + 3.45 \times IAT \text{ - } 0.51 \\ & \times \delta + 1.26 \times (TT/PT) \times RULE \text{ - } 0.73 \times BS \times RULE \\ & + 1.08 \times (TT/PT) \times BS \text{ - } 0.89 \times IAT \times BS \text{ - } 0.36 \\ & \times (ST/PT) \times RULE \text{ - } 1.20 \times (ST/PT) \times BS \text{ - } 0.75 \\ & \times IAT \times RULE \end{aligned} \qquad (2)$$

The levels of the CFs in the confirmation experiment are as follows: BS_1, TT/PT_2, $RULE_1$, ST/PT_2, TM_1, IAT_2, δ_1. Two confirmation trials were conducted and results show that the developed mathematical model is valid (Figure 5-stage5).

Refinement of the Simulation Plan and Improvement of the Mathematical Model

The refined simulation plan considers the control factors *BS*, *ST/PT*, *IAT* and δ in addition to the CFI

Figure 5. OCM application: Simulation plan with interaction (Second iteration)



Exp	$BS^{(1)}$	$RULE^{(2)}$	$TT/PT^{(4)}$	$TM^{(7)}$	$ST/PT^{(8)}$	$\delta^{(11)}$	$IAT^{(15)}$	$\frac{MFT_{FL}}{MFT_{CL}}$ Rep1	$\frac{MFT_{FL}}{MFT_{CL}}$ Rep2	S/N
1	1	1	1	1	1	1	1	0.93	0.92	-0.69
2	1	1	1	1	2	2	2	1.26	1.25	1.97
3	1	1	2	2	1	1	2	0.98	0.99	-0.13
4	1	1	2	2	2	2	1	0.94	0.96	-0.42
5	1	2	1	2	1	2	2	0.95	0.97	-0.33
6	1	2	1	2	2	1	1	1.02	1.01	0.14
7	1	2	2	1	1	2	1	0.88	0.88	-1.09
8	1	2	2	1	2	1	2	1.26	1.30	2.14
9	2	1	1	2	1	2	2	0.97	0.93	-0.47
10	2	1	1	2	2	1	1	0.91	0.94	-0.71
11	2	1	2	1	1	2	1	0.84	0.89	-1.28
12	2	1	2	1	2	1	2	1.11	1.12	0.97
13	2	2	1	1	1	1	1	0.85	0.83	-1.52
14	2	2	1	1	2	2	2	0.86	0.73	-2.06
15	2	2	2	2	1	1	2	0.98	0.97	-0.25
16	2	2	2	2	2	2	1	0.95	0.95	-0.47

STAGE 3: RESULTS OF THE ANALYSIS OF VARIANCE

Parameter	SS	DOF	MS	Pooling	DOFp	MSp	F
BS	3.40	1	3.40		1	3.40	7.54
TT/PT	0.62	1	0.62	x	–	–	–
RULE	0.45	1	0.45	x	–	–	–
ST/PT	3.33	1	3.33		1	3.33	7.40
TM	0.07	1	0.07	x	–	–	–
IAT	3.87	1	3.87		1	3.87	8.59
δ	1.05	1	1.05		1	1.05	2.33
TT/PTxRULE	1.59	1	1.59		1	1.59	3.52
BSxRULE	0.54	1	0.54	x	–	–	–
TT/PTxBS	1.17	1	1.17		1	1.17	2.59
IATxBS	0.79	1	0.79	x	–	–	–
ST/PTxRULE	0.13	1	0.13	x	–	–	–
ST/PTxBS	1.45	1	1.45		1	1.45	3.22
IATxRULE	0.57	1	0.57	x	–	–	–
ERROR	0.43	1	0.43	3.17	8	0.45	
TOTAL	19.46	15			15		

ST/PT×BS. In addition to the two studied levels, each of the three CFs was analyzed by way of a third level. This additional level corresponds to the original level as depicted in Table 1. Hence, the required TDOF is 13 [=4×2+1×4+1]. So, the $L_{27}(3^{13})$ OA was selected for the refined simulation plan and the CFs were assigned to this array using the linear graphs displayed in the Figure 6 (stages1&2). This figure depicts also the OA and the simulation results. It's worth noting that the original levels of the unused CFs in the refined plan (*RULE*, *TM* and *TT/PT)* are chosen (Table 1).

The analysis of simulation results shows that only *ST/PT* and *BS* are significant (Figure 6-stage3). This observation is confirmed by the Figure 6 (stage4) that illustrates the main effects of the CFs and CFIs. The developed mathematical model is written as follows:

$$\begin{aligned} S / N = {} & \text{-}3.83 \text{ - } 0.59 \times (ST / PT)^2 \text{ - } 0.15 \times BS^2 \text{ - } 0.12 \\ & \times IAT^2 \text{ - } 0.01 \times \delta^2 \text{ - } 0.11 \times (ST / PT)^2 \times BS^2 + 0.47 \\ & \times (ST / PT)^2 \times BS + 0.43 \times (ST / PT) \times BS^2 \text{ - } 2.17 \\ & \times (ST / PT) \times BS + 3.94 \times (ST / PT) + 0.65 \times BS \\ & + 0.68 \times IAT \text{ - } 0.06 \times \delta \end{aligned} \tag{3}$$

Table 1. Control factors

CF	Original Level	Level 1	Level 2
ST/PT	3	1	5
IAT	Exp (525) mn	Exp (420) mn	Exp (630) mn
δ	0.35	0.2	0.5
BS	38	25	50
RULE	*RL*	*RL*	*FCFS*
TM	With operations overlapping	With operations overlapping	Without operations overlapping
TT/PT	0.8 for FL ; 0.3 for CL	0.4 for FL ; 0.15 for CL	1.2 for FL ; 0.45 for CL

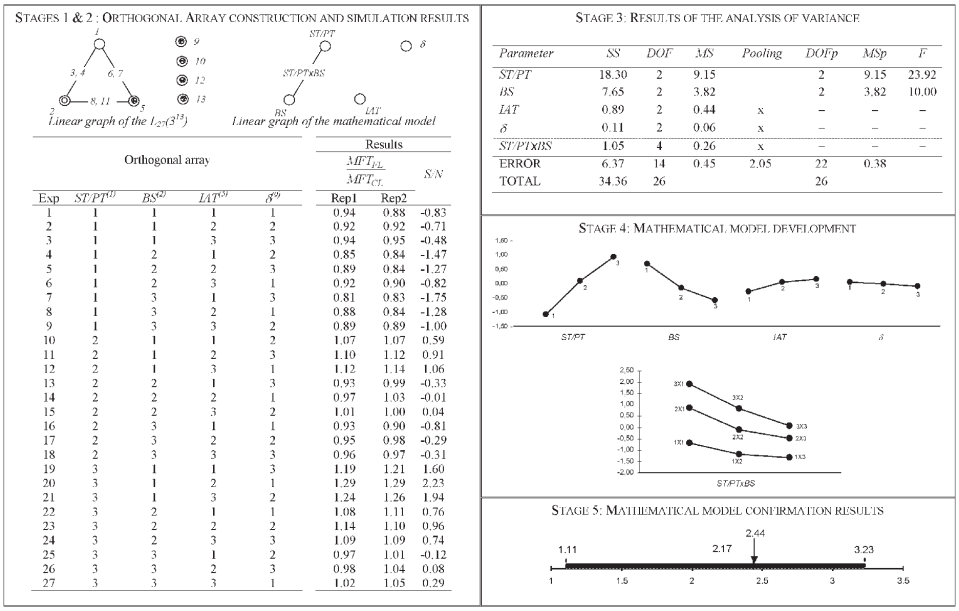
Table 2. Level combinations giving layout superiority

		IAT_1			IAT_2			IAT_3		
		δ_1	δ_2	δ_3	δ_1	δ_2	δ_3	δ_1	δ_2	δ_3
ST/PT_1	BS_1	FL	FL	FL	FL	FL	FL	FL	FL	FL
	BS_2	FL	FL	FL	FL	FL	FL	FL	FL	FL
	BS_3	FL	FL	FL	FL	FL	FL	FL	FL	FL
ST/PT_2	BS_1	CL	CL	CL	CL	CL	CL	CL	CL	CL
	BS_2	FL	FL	FL	CL	FL&CL	FL	CL	CL	FL&CL
	BS_3	FL	FL	FL	FL	FL	FL	FL	FL	FL
ST/PT_3	BS_1	CL	CL	CL	CL	CL	CL	CL	CL	CL
	BS_2	CL	CL	CL	CL	CL	CL	CL	CL	CL
	BS_3	FL	FL	FL	CL	CL	CL	CL	CL	CL

The confirmation experiment shows that the developed mathematical model is valid (Figure 6-stage5).

The MS manager can use this mathematical model to determine the best layout of its MS machines. He can also investigate the effect of the change of one or several CFs levels on performances of the two layouts. In fact, if the computed *S/N* ratio value is negative then the FL is the outperforming layout. In contrary, if the predicted *S/N* ratio value is positive then the CL outperforms the FL. Finally, the two layouts performances are considered equivalents if the *S/N* ratio value predicted by the mathematical model is close to zero. Table 2 depicts the CL and FL superiority contexts expressed as combinations of the CFs.

Figure 6. OCM application: Refined simulation plan



STAGES 1 & 2 : ORTHOGONAL ARRAY CONSTRUCTION AND SIMULATION RESULTS

Orthogonal array					Results		
					$\frac{MFT_{FL}}{MFT_{CL}}$		S/N
Exp	$ST/PT^{(1)}$	$BS^{(2)}$	$IAT^{(5)}$	$\delta^{(9)}$	Rep1	Rep2	
1	1	1	1	1	0.94	0.88	-0.83
2	1	1	2	2	0.92	0.92	-0.71
3	1	1	3	3	0.94	0.95	-0.48
4	1	2	1	2	0.85	0.84	-1.47
5	1	2	2	3	0.89	0.84	-1.27
6	1	2	3	1	0.92	0.90	-0.82
7	1	3	1	3	0.81	0.83	-1.75
8	1	3	2	1	0.88	0.84	-1.28
9	1	3	3	2	0.89	0.89	-1.00
10	2	1	1	2	1.07	1.07	0.59
11	2	1	2	3	1.10	1.12	0.91
12	2	1	3	1	1.12	1.14	1.06
13	2	2	1	3	0.93	0.99	-0.33
14	2	2	2	1	0.97	1.03	-0.01
15	2	2	3	2	1.01	1.00	0.04
16	2	3	1	1	0.93	0.90	-0.81
17	2	3	2	2	0.95	0.98	-0.29
18	2	3	3	3	0.96	0.97	-0.31
19	3	1	1	3	1.19	1.21	1.60
20	3	1	2	1	1.29	1.29	2.23
21	3	1	3	2	1.24	1.26	1.94
22	3	2	1	1	1.08	1.11	0.76
23	3	2	2	2	1.14	1.10	0.96
24	3	2	3	3	1.09	1.09	0.74
25	3	3	1	2	0.97	1.01	-0.12
26	3	3	2	3	0.98	1.04	0.08
27	3	3	3	1	1.02	1.05	0.29

STAGE 3: RESULTS OF THE ANALYSIS OF VARIANCE

Parameter	*SS*	*DOF*	*MS*	*Pooling*	*DOFp*	*MSp*	*F*
ST/PT	18.30	2	9.15		2	9.15	23.92
BS	7.65	2	3.82		2	3.82	10.00
IAT	0.89	2	0.44	x	–	–	–
δ	0.11	2	0.06	x	–	–	–
ST/PTxBS	1.05	4	0.26	x	–	–	–
ERROR	6.37	14	0.45	2.05	22	0.38	
TOTAL	34.36	26			26		

STAGE 4: MATHEMATICAL MODEL DEVELOPMENT

STAGE 5: MATHEMATICAL MODEL CONFIRMATION RESULTS

This table can be used by the manager to determine the more effective layout for every one of the 81 possible level combinations of the four considered CFs. In deed, the intersection between the line that represents the combination of the *ST/PT* and *BS* levels and the column corresponding to the *IAT* and δ levels gives the best performing layout. For example, the CL is the best layout for the following CFs levels combination: ST/PT_2, BS_1, IAT_2 and δ_2.

The mathematical model can also be used to predict the best layout for "intermediate levels" of the CFs *ST/PT*, *BS*, *IAT* andδ. Indeed unlike the *TM* and *RULE* CFs which are discrete and can be investigated only for specified levels, *ST/PT*, *BS*, *IAT* andδ are continuous factors. For example for the following setting combination: $ST/PT_{1.5}$, $BS_{2.2}$, $IAT_{1.4}$ and $\delta_{2.4}$ the FL outperforms the CL. In this case, le level X_i of the CF X is obtained by linear interpolation between the different levels of this CF.

CONCLUSION

This chapter presents an objective methodology for comparing functional and cellular layouts. This methodology aims to help MS managers choosing the appropriate layout for their manufacturing system. The developed methodology is based on the Taguchi method for the design of experiments and results analysis combined to discrete event simulation. This method permits, through a minimal experimental effort, to reliably evaluate the effect of each MS parameters on the system performances. It also reveals the possible interactions between MS parameters. The goal of this methodology is the development of a mathematical model predicting the superiority of one 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. The sign of the predicted *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. An academic case study showed the capacity of this methodology for choosing the best layout for a MS.

The developed methodology can find direct applications in the industry. However, many aspects of the comparison methodology should undergo further developments. The first task is the enlargement of the application scope to other control factors such as various levels of the number of operators or different degrees of the operator's qualification. In addition, in order to minimize the effort provided by the MS manager, the automation of coupling between the simulator and the analyze software 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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