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APPLICATION OF DESIGN OF EXPERIMENTS ON THE SIMULATION OF A PROCESS IN AN AUTOMOTIVE INDUSTRY

José Arnaldo Barra Montevechi

Avenida BPS, 1303 – Caixa Postal: 50
Instituto de Engenharia de Produção e Gestão
Universidade Federal de Itajubá
Itajubá, MG, 37500-903, BRAZIL

Alexandre Ferreira de Pinho
Fabiano Leal
Fernando Augusto Silva Marins

Av. Dr. Ariberto Pereira da Cunha, 333
Universidade Estadual Paulista
Guaratiguetá, SP, 12.516-410, BRAZIL

ABSTRACT

The objective of this article is to apply the Design of experiments technique along with the Discrete Events Simulation technique in an automotive process. The benefits of the design of experiments in simulation include the possibility to improve the performance in the simulation process, avoiding trial and error to seek solutions. The methodology of the conjoint use of Design of Experiments and Computer Simulation is presented to assess the effects of the variables and its interactions involved in the process. In this paper, the efficacy of the use of process mapping and design of experiments on the phases of conception and analysis are confirmed.

1 INTRODUCTION

As an example of conjoint application of simulation and design of experiments, the work of Nazzala *et al.* (2006) can be cited, as it integrates simulation, design of experiments and economic analysis in a decision-making process at a semiconductors company, using a simulation model validated according to techniques presented by Law and Kelton (2000), Nayani and Mollaghasemi (1998), Sargent (1998).

The benefits of the design of experiments in simulation include the possibility of improving the performance on the simulation process, avoiding the trial-and-error techniques to seek solutions. Kleijnen *et al.* (2005) affirm that research related to design of experiments is frequently found in specialized magazines, rarely read by simulation practitioners.

Thus, the objective of this article is to apply the design of experiments techniques along with the discrete events simulation technique in a process of an automotive industry. The effect of the input variables (buffer capacity, number of tables, pre-plug operation time and assembly table operations time) over the output variable (total of parts produced) is intended to be evaluated. Moreover, the effects of the interaction between the input variables through complete factorial design is also intended to be assessed.

2 COMPUTER SIMULATION IN MANUFACTURING ENVIRONMENTS

According to Harrell *et al.* (2000), and Law and Kelton (1991), simulation is the imitation of a real system, computer-modeled, for evaluation and improvement of its performance. In other words, simulation is the importing of reality to a controlled environment where its behavior can be studied, under various conditions, without physical risks and/or large costs involved. Banks (2000) affirms that simulation involves the creation of an artificial history of reality and, based on this artificial history, observations and inferences on the operating characteristics of the real system that is represented can be made.

O'Kane *et al*. (2000) affirm that simulation has become one of the most popular techniques to analyze complex problems in manufacturing environments.

According to Banks *et al.* (2005), simulation is one of the most widely used tools in manufacturing systems, more than in any other area. Some reasons may be enumerated:

a) The increase in productivity and quality in the industry is a direct result from automation. As automation systems become more and more complex, they can only be analyzed using simulation;
b) The costs with equipment and installations are huge;
c) Computers are becoming cheaper and faster;
d) Improvements on simulation software reduced the time of development of models.
e) The availability of animation resulted in higher comprehension and usage from manufacturing managers.

3 DESIGN OF EXPERIMENTS

The word experiment is used in a very precise form to indicate an investigation where the system under study is under control of the investigator. On the contrary, for an observational study, some characteristics will be out of the control of the investigator. (Cox and Reid 2000). According to Montgomery (2001), the experiment can be seen as a test, or as a series of tests, in which the proposed changes are applied on the input variables of a process or system, to, then, observe and identify the changes occurred on the output variables.

Still according to Montgomery (2001), the design of experiments refers to the process of planning of experiments in a way that appropriate data can be analyzed through statistical methods, resulting in valid and objective conclusions. According to Kelton (1999), one of the main goals of the experimental design is to estimate how changes in input factors affect the results, or answers of the experiment.

Some terms are commonly used in design of experiments. Mason *et al.* (2003) define “factor” as a controllable experimental variable, which variation influences the response variable. Each factor must assume some values, defined as levels. The changes occurred on the mean of the values of the response variable correspond to the effects.

Besides the effects caused by the factors, the effects created by the interaction of the factors can be determined. These interactions correspond to combined effects, where the effect of each factor depends on the levels of the other factors.

The decisional process of the experimentalist falls back on a trade-off between performance versus cost, where the necessity of a more precise recognition of a greater number of factors and interactions bears a larger number of experiments and replicates.

According to Cox and Reid (2000), the advantages of the use of a complete factorial lies on the higher efficiency in estimating the main effects of the factors under the variable in analysis, and, specially, the definition of the interaction among all the factors.

According to Sanchez *et al.* (2006), many studies related to operations management use the full factorial design of experiments because of its simplicity and due to the fact that its project allows the analyst to identify interactions among the factors, as well as the main effects. As examples of these studies works from Enns (1995), who used the factorial design to evaluate the usage rate and sequencing techniques in a process can be mentioned. Malhotra and Ritzman (1994) considered a 2^4 factorial design to evaluate the impact of demand variability, usage capacity, and route flexibility in postal service stations.

The disadvantage of the use of the complete factorial lies on the amount of time and experiments to be made. According to Kelton (1999), when the number of factors becomes moderately large, the number of experiments explodes. A possible solution for this situation is the use of fractional factorial, in which only a fraction of all possible combinations are evaluated. This solution is indicated to situations where a great number of factors to be analyzed exist, where only the main effects of the factors are considered important.

The realization of the experiments is frequently expensive or even impracticable. For these situations, the use of simulated experiments is recommended, and this integration between design of experiments and simulations is presented as follows.

4 DESIGN OF SIMULATED EXPERIMENTS

According to Kelton (1999), the use of simulation aids directly the execution of experiments that are costly or even impossible to be carried out in practice. Still illustrating the conjoint applicability of design of experiments and simulation, Barton (2002) points out in his work that, typically, simulation researchers emphasize the realization of experiments on the simulator and the analysis of the responses obtained, not paying attention to a previous phase to this one, where the planning of the experiment to be carried out must be made, with the possibility of being carried out in practice through DOE.

According to Kleijnen *et al.* (2005), many simulation practitioners could obtain more information from their analysis if they used statistical theories, more specifically with the use of design of experiments developed specifically for computer models.

To understand the role of simulation in the execution of experiments, it is only necessary to imagine that, in an experiment, the response variable (RV), or dependent variable, can be represented as: RV = f (IV), where IV represents the input variables (independent variables). Thus, according to Kelton (1999), the transformation function f represents the simulation model itself.

Nowadays, simulation software accompanies generators of random numbers. So, according to Kelton (1999), from the design of experiments point of view, it is possible to excerpt the experimental randomization, that frequently corresponds to a hard problem in physical experiments. Another important verification is that, when the execution of the experiments occurs in a simulation model, all the input factors became controllable. Barton (2002) emphasizes this statement affirming that nuisance variables rarely appear in simulation models, because normally, there is control over all other factors.

Another important advantage of the use of simulation in the execution of experiments is replicating the experiments many times, obtaining many estimates of the main effects and interaction of the factors. These replicates will favor the conclusion of the significance or nonsignificance of the effect. Frequently, physical experiments are made in a small number of replicates, or even without them, due to the experiment difficulty or even the cost involved. These limitations do not occur in simulation once the model is constructed and validated.

Dessouky and Bayer (2002) integrated the selection of the maintenance policy in the process construction phase, through simulation (software ProModel 4.0) and application of DOE, through the Taguchi technique.

In this research, 4 factors (problem severity, maintenance policy, resource capacity and validation time) and 2 levels were defined. The experience of the specialists and the system knowledge were used to define the factors and variables.

Schappo (2006) presents an analysis of an assembly process of compressors and cellular layout alternatives, making use of design of experiments techniques and computer simulation as an analysis tool of the different scenarios with the objective of quantitatively measuring the changes introduced on the system which is being studied, improving the performance indicators in the manufacturing process as well as productivity increase.

In the opinion of Kleijnen *et al.* (2005), most projects were originally developed for experimentation in the real world, and they have been adapted to be used in simulation studies, instead of being developed specifically inside the simulation principles. Classical texts of design of experiments, such as Box *et al.* (1978), Box and Draper (1987), Montgomery (2001), Myers and Montgomery (2002), focus not on the necessity of simulation analysts, but on the practical restrictions and conduction of experiments in the real word. Other texts about simulation such as Law and Kelton (2000) and Banks *et al.* (2005) cover a vast array of topics on the subject, however the demonstration of design of experiments is done using simpler problems, that do not stimulate the mental abstraction of readers about the deepness and application possibilities.

Therefore, it may be affirmed that practitioners of simulation must be attentive to the use of experiment projects as a necessary part of the analysis of complex simulations.

5 METHODOLOGY

According to Silva and Menezes (2005), a research is experimental when an object of study is determined, variables that would be capable of influencing it are selected, and ways of controlling and observing the effects that the variable produces on the object are defined. On this experimental research, the experiments will be carried out through a discrete events simulation.

Using an analysis of the simulation methodology proposed by Chwif (1999) and the steps proposed by Montgomery (2001) for design of experiments, a flowchart that tries to explain the logic of the simulation process was constructed, in which the experimentation phase is conducted by DOE. This research was conducted according to the methodology shown in figure 1. In this methodology, there are three models that must be made: the conceptual model, the computer model and the operational model. In the same manner, these models must be validated or verified. According to Law (1991), the creation phase of the conceptual model is the most important aspect in a study of simulation. Chwif and Medina (2006) dedicate special attention to this model, since, according to them, many simulation researches do not demonstrate this stage. According to Shannon (1975), an effective conceptual modeling can lead to the identification of an adequate solution, avoiding the necessity of a complete simulation study. Works such as Greasley (2006) use process mapping as a means of describing the logic and determining decision points, even before the computer model, created in the software ARENA.

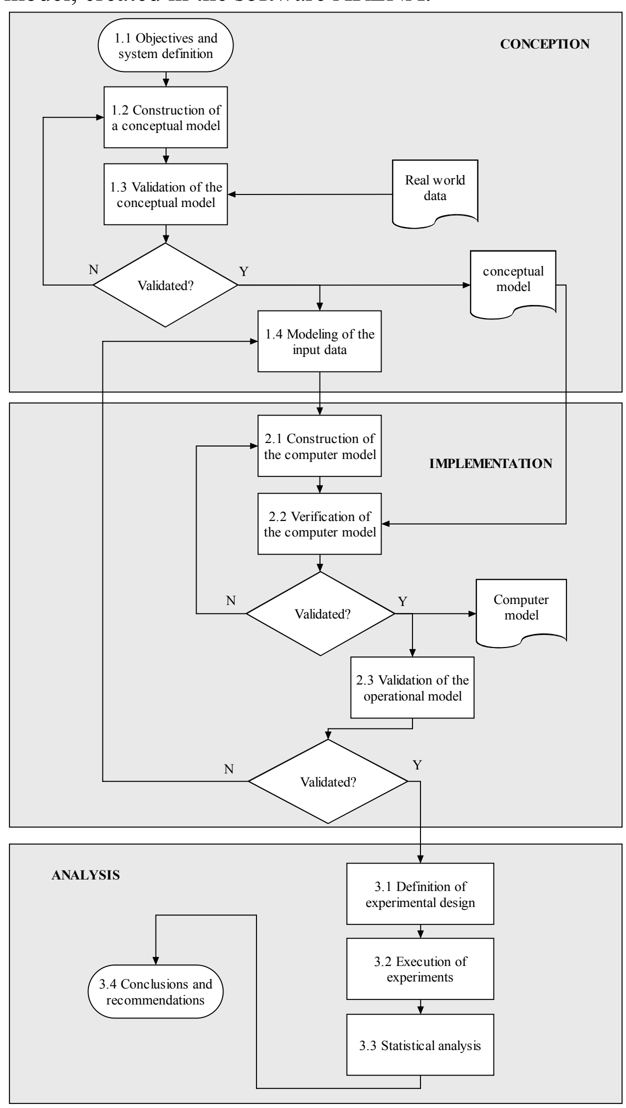

Figure 1: Methodology of conduct of this research

In this paper, the conceptual model will be the starting point, supplying information to the computer model. The representation of the conceptual model will be made in the form of a process mapping, executed using a selected technique. According to Leal (2003) and Pinho *et al.*(2006), these techniques must be selected according to the characteristics of the process and the objectives of the work. Besides, the generated maps must not be characterized as an end, but as a feasible means for visualizing improvements.

In this research, the process map will be used, which, according to Barnes (1982), is a technique to register a process in a compact way, through some standardized symbols like operations, transports, inspections, delays and warehousing. The level of detail achieved by this technique is compatible with the objective of this research. Moreover, it is a well-known tool, which facilitates the validation process of the conceptual model, along with process specialists (real system).

The computer model is obtained through conversion of the conceptual model using some simulation language or a commercial simulator.

The simulator selected for this work is PROMODEL. Hlupic and Paul (1996) present a methodological approach to select the simulation software, according to some criterion, as cost and processing time. The reasons for choosing this software for this research are due to, above all, the use of graphic animation, an important ally in the verification and validation of the model. In the same manner, works from authors such as Verma *et al.* (2000) justify the use of PROMODEL due to the possibility to analyze the simulation through the accompaniment of the animation, being easy to apply and interpret.

After the elaboration of the computer model, it must be verified whether its behavior is according to the conceptual model. This process is called model verification. The verification also consists of eliminating bugs from the model.

After obtaining and verifying the computer model, it must be submitted to various runs obtaining, this way, results in different scenarios. These results must be compared with the results of a real system, in order to verify the size of the error. Once the error is inside the acceptable limits, the model is apt execute experiments, defined on the planning carried out via DOE.

6 APPLICATION OF THE PROPOSED METHODOLOGY

The way the steps of the proposed methodology of the above item were conducted during this research will be described as follows.

Step 1.1: Objectives and system definition

The objective of this work is determining which variables, among the selected, have more influence over the total production of the productive system. The four analyzed variables were: number of assembly tables, buffer capacity, pre-plug operation time, and operation time of the assembly tables. These variables were selected because they were pointed out by the specialists of the real system as strategic.

For the execution of this study, an assembly line in a company from the automotive sector producer of electronic components was determined.

The productive system which the study focuses produces four part families, totaling 900 parts daily. However, for research purposes, one product family was chosen, referring to the production of 549 units a day. Such choice is justified by the fact that this part family embodies a larger number of processes, besides belonging to the classification A, in terms of ABC inventory classification.

Step 1.2: Construction of a conceptual model

In this phase, the real model under investigation is summarized using the conceptual model, which is simply a series of logical relationships relative to the components and structure of the system.

The process mapping of the real system is shown on figure 2. After having its production designated, the first operator takes off the necessary components from the stocking point and makes the initial circuit. After that, the parts go to the pre-plug tables where they receive some parts. Soon after, they go to the final circuit. Then, the product is called subassemblies and the final assembly is undertaken. The conveyor sends each part to the electric test, visual inspection, and finally, packaging.

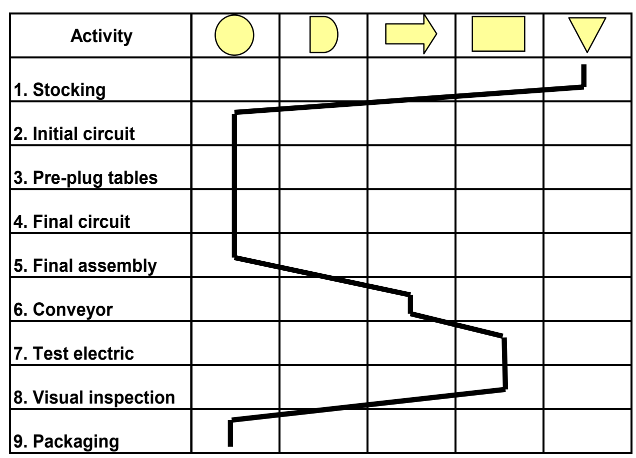

Figure 2: Process mapping of the real system to be simulated

Step 1.3: Validation of the conceptual model

The validation was realized through comparison between the process mapping and the real situation. The mapping, realized by the researchers, was presented to the process specialists and to people from the company not directly related to the real system. This way, once verified that the system is correctly represented, the conceptual model is registered.

Step 1.4: Modeling of the input data

For the realization of this work, the software Promodel® from Promodel Corporation was used. It is one of the most used softwares on the market (Doloi and Jafari, 2003). This package incorporates three main programs: Promodel® (for simulation of discrete events), SimRunner® (for the optimization of optimization models), and Stat::Fit® (for probability distribution studies).

The processing times were measured in the object of study and inserted in the software Stat::Fit® with the objective of obtaining the candidate probability distributions and the adherence test.

Step 2.1: Construction of a computer model

The information required from the object of study for the construction of computer models were defined as: Amount of parts produced; Daily demand in the months of April, May, June, and July; Lot size; Number of operators, Takt time, Setup times, Number of machines and production capacity; Production lead times, Production triggers, Average inventory time in supermarkets.

For the construction of a model, ProModel® presents the following elements: places, entities, resources, processing and arrivals. The definitions and the functionality of the main elements are shown as follows:

Places: Represent the fixed places of the system, where the processes are carried out. These elements are used for the representation of workstations, buffers, conveyors and waiting lines. In this element, capacity, units (simple or multiple), setups, maintenance, statistical detail level and rules for the arrival and departure of materials can be defined.

Entities: The entities are items to be processed by the system, and they can be: raw material, pallets, people, or documents. The entities have defined speed, besides having statistical level like the places. They can be grouped or divided along the productive process, being moved from one place to another using a defined route or a work network.

Variables: Can be global or local. The global variables are used to represent mutable numeric values. The local variables only establish functions in the part of logic in which they are declared, and both can contain either numerical or real values. A global variable can be referred to in any place of the model. On the other hand, the local variable can only be referred to inside a determined block where it has been declared.

Attributes: Similar to the variables, the attributes are attached together with entities and specific places and usually contain information about them. They can contain real or whole numbers. From its usage only one entity referring to one type of part can be created and seven attributes to differentiate the seven types of parts to be modeled, as occurs in this paper.

Arrivals: Defines the input of the entities inside the model. The quantities, frequency, arrival periods as well as the arrival logic can be defined. Also, the arrivals through an external arrival file of parts referred to in the file editor can be defined.

Processing: Consists of a table where the operations of each entity in each place as well as the necessary resource for this operation, and a table of routes that determines the destiny and movement of each entity as well as the way in which this movement happens and the necessary resources are defined.

Resources: Are the elements used to transport entities, execute operations, make place maintenance. They can be either people or equipment. A system can have one or more resources, endowed with movement or not. However, for each mobile resource a path network must be designated, that is, a route in which movement will happen.

Figure 3 illustrates the construction environment of the computer model from ProModel®.

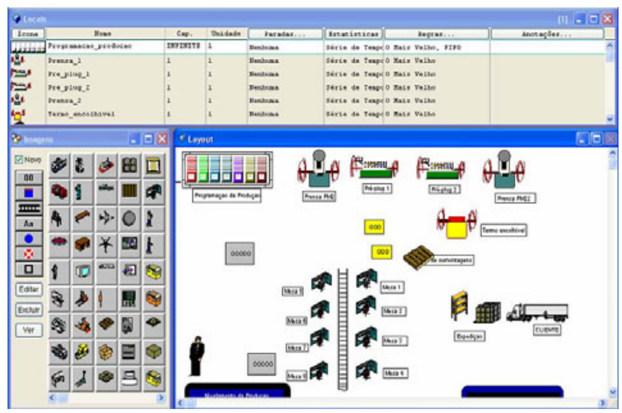

Figure 3: Environment of the computer model from Promodel®

Step 2.2: Verification of the computer model

Some runs are carried out to verify if the model follows the logic pointed out in the conceptual model. Programming errors must be identified in this phase. Once the verification of the model is successfully completed, the computer model is documented.

Step 2.3: Validation of the operational model.

Validating a model is assessing how close it is to the real system, assuring that the model serves the purpose it was created. An attempt to validate the model was made, through comparison of the real system result with the simulated model and through direct confrontation of these results with historic data of the productive system under study. Table 1 illustrates this comparison.

Table 1: Real x virtual comparison

	Real model	Simulated model
Daily average of produced parts	549	522
Takt time	55s	58s
Places	18	18
Parts	7	7

Another form of validation used was through the total amount produced in the modeled months of May, June, and July, since the data from the month of April was not made available by the company. Table 2 shows the comparison of the real production with the simulated production. Once the model is validated, it is possible to carry out the experimentation phase.

Table 2: Comparison of the real production versus the simulated production

Total Production		
Months	Real	Simulated
May	10357	10500
June	9616	8681
July	10643	8895

Step 3.1: Definition of Experimental design

The factors selected for the work correspond to those the team defined as most probable of having contribution in the total amount of parts produced by the system.

Factor A: Buffer capacity: This factor expresses the amount of parts arranged on the subassembly pallets, providing an elevated operating level to the operating tables and the compliance to the takt time of 50 seconds. The phase of the process before the buffer works one hour ahead in relation to the rest of the process.

Factor B: Number of assembly tables: This factor measures the number of assembly tables situated around the conveyor, which are responsible for the number of parts produced daily. When an amount smaller than 500 parts is desired, the system works with a number of tables smaller than 8, as 6 or 4 for example.

Factor C: Pre-plug operating time: This factor measures the operating time of the pre-plug operating tables, responsible for the settlement of components. Their capacities are dimensioned to meet the average daily demand of 549 parts.

Factor D: Assembly table operating time: Responsible for the number of pieces produced daily, as said before. And, consequently, it has great importance in the productive process. The use of its operating times with probability distributions has as objective to obtain a behavior of this phase of the system focus of this study as close as possible from reality.

In summary, the experiment planning is as follows:

- Number of Factors: 4;
- Number of Levels: 2;
- Number of Experiments: 16;
- Number of Replicates: 3.

Table 3 shows the experimental conditions for the described experiment..

Table 3: Experimental conditions

Factors	Level +	Level -
A: Buffer Capacity (units)	60	100
B: Number of tables (units)	4	8
C: Pre-plug operating time (min/part)	0,6	0,9
D: Table time of operation (min/part)	N(6,35 ; 0,66)	N(7,35 ; 0,66)

Step 3.2: Execution of the Experiments

Table 4 shows the experimental matrix for the experiment planning described on step 3.1.

Table 4: Experimental matrix

	A	B	C	D	r1	r2	r3	Média	S
1	-	-	-	-	303	299	300	300,67	4,33
2	+	-	-	-	304	298	300	300,67	9,33
3	-	+	-	-	304	298	299	300,33	10,33
4	+	+	-	-	304	298	299	300,33	10,33
5	-	-	+	-	301	297	299	299,00	4,00
6	+	-	+	-	301	297	298	298,67	4,33
7	-	+	+	-	511	512	511	511,33	0,33
8	+	+	+	-	538	538	538	538,00	0,00
9	-	-	-	+	261	259	259	259,67	1,33
10	+	-	-	+	261	261	260	260,67	0,33
11	-	+	-	+	435	436	434	435,00	1,00
12	+	+	-	+	514	509	518	513,67	20,33
13	-	-	+	+	261	260	258	259,67	2,33
14	+	-	+	+	261	260	258	259,67	2,33
15	-	+	+	+	488	487	491	488,67	4,33
16	+	+	+	+	510	507	515	510,67	16,33
							Total	5836,67	91,33

Step 3.3: Statistical Analysis

The analysis of the main effects of each factor, presented in figure 4, shows that factor B (number of tables) has a strong positive effect over the final response, that is, the amount produced. This means that the alteration of level (-) to level (+) increases the final result. MiniTab® was the software used for the developed calculations.

The weight of the effects can be visualized in figure 5. On this graph, it can be verified that all the factors and its interactions are significant for a degree of confidence of 95%, as showm by cutoff line for statistical significance. Factor B (number of tables) is the most significant, followed by the interaction BC (number of tables * pre-plug operations time), by factor C (pre-plug operations time), by the interaction BD (number of tables * table operating time), by the interaction BCD (number of tables * pre-plug operations time * table operating time), and by interaction CD (pre-plug operations time * table operating time).

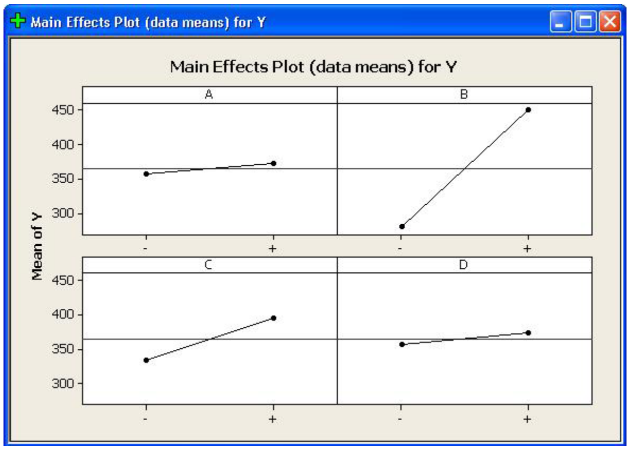

Figure 4: Graph of the main effects

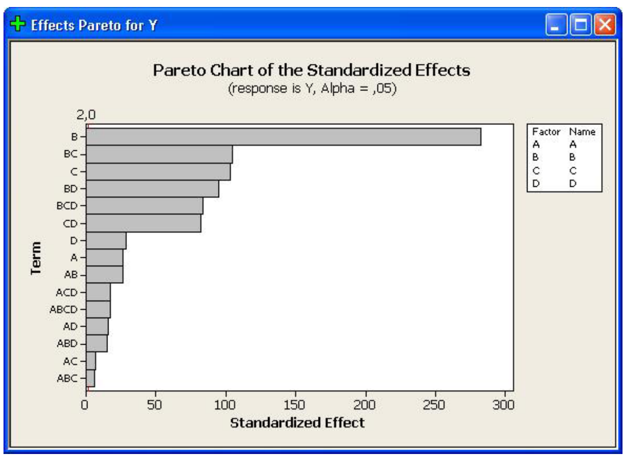

Figure 5: Pareto chart of the standardized effects

Step 3.4: Conclusions and Recommendations

The occurrence of interaction with significant effects (BC, BD, BCD and CD) imposes the necessity of analysis of the interactions. The second order interactions are shown in figure 6, and it is possible to confirm the interaction between these factors.

Based on the results shown on the previous item, it can be concluded that among the factors analyzed in this experiment, factor B is the one that influences most significantly the response variable *parts produced*. Moreover, the interactions between factors BC, BD, BCD and CD also influences significantly the response variable.

It's important to highlight the factor D has almost no impact as a main effect, but is involved in interactions.

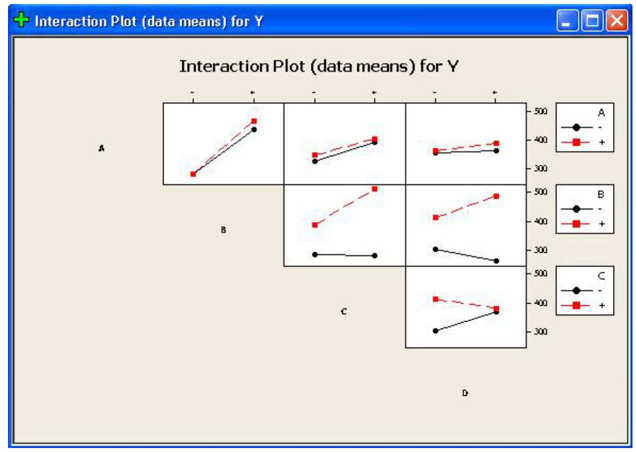

Figure 6: Second order interaction between the factors

7 CONCLUSION

The use of Design of Experiments conjointly with Computer Simulation allowed a more efficient analysis of the results of the simulated model. Moreover, the significance of the effects of the interactions were confirmed, aiding the managerial decision making process.

It is also important to emphasize that the process mapping technique made possible the creation of the conceptual model in the conception phase of the used methodology, as shown in figure 1. The same way, the Design of Experiments technique made possible a more meticulous analysis in the analysis phase.

For the company, the recognition of the individual and combined effects of the factors favors the elaboration of an improvement plan for the increase of the daily production rate. Since the productive process is dynamic, that is, it is altered according to market demand, knowing the most relevant factors of this process facilitates the decision making, about the factor levels, by the managers.

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REFERENCES

Banks, J., J. S. Carson, B. L. Nelson, and D. M. Nicol, 2005. *Discrete-event Simulation*, Quarta edição, Prentice-Hall, Upper Saddle River, NJ, New Jersey: Prentice-Hall, Inc.

Barnes, 1982. R. M. Estudo de movimentos e de tempos. São Paulo: Edgard Blücher, 6ª ed.

Barton, R. R. 2002. Designing simulation experiments. In *Proceedings of the 2002 Winter Simulation Conference* 45-51. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Box, G. E. P., and R. Draper. 1987. *Empirical Model-Building with Response Surfaces*. Wiley, New York,

Box, G. E. P., W. G. Hunter, and J. S. Hunter. 1978. *Statistics for Experimenters: An Introduction to Design, Data Analysis and Model Building*. Wiley, New York.

Chwif, L. 1999. *Redução de modelos de simulação de eventos discretos na sua concepção: uma abordagem causal*. Tese de doutorado. Escola Politécnica da USP, Departamento de Engenharia Mecânica.

Chwif, L., and A.C. Medina. 2006. *Modelagem e Simulação de Eventos Discretos: Teoria e Aplicações*. São Paulo, Ed. Dos Autores.

Cox, D.R., and N. Reid. 2000. *The Theory of the Design of Experiments*. Chapman & Hall/CRC.

Dessouky, Y.M., and A. Bayer. 2002. A simulation and design of experiments modeling approach to minimize building maintenance costs. *Computers & Industrial Engineering* 43

Doloi, H., and A. Jaafari. 2003. Conceptual simulation model for strategic decision evaluation in project management. *Logistics Information Management* 15(2)

Enns, S.T. 1995. An integrated system for controlling work load and flow in a job shop. *International Journal of Production Research* 33: 2801–2820

Greasley, A. 2006. Using process mapping and business process simulation to support a process-based approach to change in a public sector organization. *Technovation* 26 : 95-103

Harrell, C. R., B. K. Ghosh, and R. Bowden 2000. Simulation Using Promodel. McGraw-Hill.

Hlupic, V., and R.J. Paul, 1996. Methodological approach manufacturing simulation selection. *Computer Integrated Manufacturing Systems* 9(1) : 49-55.

Kelton, W. D. 1999. Designing simulation experiments. In *Proceedings of the 1999 Winter Simulation Conference* 33-38. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Kleijnen, J. P. C., S. M. Sanchez, T.W. Lucas, and T. M. Cioppa. 2005., State-of-the-Art Review: A User's Guide to the Brave New World of Designing Simulation Experiments. *Journal on Computing* 17(3) : 263–289.

Law, A. 1991. Simulation model´s level of detail determines effectiveness. *Industrial Engineering* 23(10) : 16-18.

Law, A. M., and W. D. Kelton. 2000. *Simulation Modeling and Analysis*, 3rd ed. McGraw-Hill, New York.

Leal, F. 2003. *Um diagnóstico do processo de atendimento a clientes em uma agência bancária através de mapeamento de processos e simulação computacional*. Dissertação (Mestrado em Engenharia de Produção) Programa de Pós-Graduação em Engenharia de Produção, Itajubá, MG, UNIFEI.

Malhotra, M. K., and L. P. Ritzman. 1994. Scheduling flexibility in the service sector: a postal case study. *Production & Operations Management,* 3, 100–117.

Mason, R. L., R. F. Gunst, and J. L. Hess. 2003. *Statistical Design and Analysis of Experiments*. John Wiley & Sons Publication.

Montgomery, D. C. 2001. *Design and Analysis of Experiments*, 5th edition, John Wiley & Sons, Inc.

Myers, R. H., and D. C. Montgomery 2002. *Response Surface Methodology: Process and Product Optimization using Designed Experiments*, Segunda edição, Wiley, New York.

Nayani, N., and M. Mollaghasemi 1998. Validation and verification of the simulation model of a photolithography process in semiconductor manufacturing. In *Proceedings of the 1998 Winter Simulation Conference* 1017-1022. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Nazzala, D., M. Mollaghasemi, and C. D. Anderson 2006. A simulation-based evaluation of the cost of cycle time reduction in Agere Systems wafer fabrication facility - a case study. *International Journal of Production Economics* 100: 300–313.

O'Kane, J.F., J. R. Spenceley, and R. Taylor 2000. Simulation as an essential tool for advanced manufacturing technology problems. Journal of Materials Processing Technology 107: 412-424.

Pinho, A. F., F. Leal, and D. A. Almeida. 2006. A Integração entre o Mapeamento de Processo e o Mapeamento de Falhas: dois casos de aplicação no setor elétrico. *Anais do XXVI ENEGEP – Encontro Nacional de Engenharia de Produção*, Fortaleza, Ceará, Brasil.

Sanchez, S. M., F. Moeeni, and P. J. Sanchez. 2006. So many factors, so little time: Simulation experiments in the frequency domain. *International Journal of Production Economics* 103: 149–165.

Sargent, R. G. 1998. Verification and validation of simulation models. In *Proceedings of the 1998 Winter Simulation Conference* 121-130. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Schappo, A. J. 2006. Um método utilizando simulação discreta e projeto experimental para avaliar o fluxo na manufatura enxuta. *Dissertação submetida ao programa de Pós Graduação em Engenharia de Produção e Sistemas da Universidade Federal de Santa Catarina*, Florianópolis.

Shannon, R. E. 1975. *Systems simulation: the art and science*. Englewood Cliffs: Prentice-Hall.

Verma, R., G. D. Gibbs, and R. J. Gilgan 2000. Redesigning check-processing operations using animated computer simulation. *Business Process Management* 6(1) :54-64.

AUTHOR BIOGRAPHIES

JOSÉ ARNALDO BARRA MONTEVECHI is a Titular Professor of Instituto de Engenharia de Produção e Gestão at Federal University of Itajubá, in Brazil. He holds the degrees of Mechanical Engineer from Federal University of Itajubá and M.Sc. in Mechanical Engineer from Federal University of Santa Catarina, and Doctorate of Engineering from Polytechnic School of University of São Paulo. His research interest includes Operational Research, Simulation and Economic Engineering. His e-mail address is <montevechi@unifei.edu.br>.

ALEXANDRE FERREIRA DE PINHO is a Professor of Instituto de Engenharia de Produção e Gestão at Federal University of Itajubá, in Brazil. He holds the degrees of Mechanical Engineer from Federal University of Itajubá and M.Sc. in the same university. His research interest includes Operational Research, Simulation and Operations Management. His e-mail address is <pinho@unifei.edu.br>.

FABIANO LEAL is a Professor of Instituto de Engenharia de Produção e Gestão at Federal University of Itajubá, in Brazil. He holds the degrees of Mechanical Engineer from Federal University of Itajubá and M.Sc. in the same university. His research interest includes Simulation, Operations Management and Work Study. His e-mail address is <fleal@unifei.edu.br>.

FERNANDO AUGUSTO SILVA MARINS is a Professor of Engineering College – Campus of Guaratinguetá – São Paulo State University, in Brazil. He holds the degree of Mechanical Engineer from São Paulo State University, the M.Sc. in Operations Research from Institute Technological of Aeronautics, and PhD in Operations Research from State University of Campinas. His research interest includes Operational Research, Simulation and Logistics. His e-mail address is <fmarins@feg.unesp.br>.