DOI: 10.5585/ExactaEP.v13n2.5850

Optimization of a semiconductor manufacturing process using a reentrant model

Otimização do processo de manufatura de semicondutores utilizando um modelo reentrante

Sarah Abuhab Valente
Graduada em Engenharia de Gestão pela Universidade Federal do ABC – UFABC, Mestranda em Engenharia pela Northeastern University.
Boston, Massachussetts [U.S.A.]

Eduardo Christiano Cecone
Docente e Pesquisador, Engenheiro de Materiais com especialização em Qualidade e Produtividade, Mestrando em Energia pela Universidade Federal do ABC – UFABC. Santo André, SP [Brasil]

Luiz Alberto Paoliello Alvim
Graduado em Engenharia Mecânica pelo Centro Universitário da FEI e Mestre em Engenharia Mecânica pela Escola Politécnica da Universidade de São Paulo – EPUSP, Coordenador do curso de Engenharia e Professor da Universidade Anhanguera de São Paulo – UNIAN, Campus ABC.
São Bernardo do Campo, SP [Brasil]
luiz.alvim@anhanguera.com

Douglas Alves Cassiano
Docente e Pesquisador, Doutor em Engenharia pela Universidade Estadual de Campinas – Unicamp, com ênfase em Simulação e Otimização Matemática, Professor na Universidade Federal do ABC – UFABC.
Santo André, SP [Brasil]

Abstract

The scope of this work is the simulation of a semiconductor manufacturing model in Arena® software and subsequent optimization and sensitivity analysis of this model. The process is considered extremely complex given the amount of steps, machinery, parameters, and highly reentrant characteristics, which makes it difficult to reach stability of production process. The production model used was the Intel Five-Machine Six-Step Mini-fab developed by Karl Kempf (1994). It was programmed in Arena® and optimized by OptQuest®, an add-on. We concluded that variation in the number of machines and operators reflects on cycle time only if there is an increase of one unit of resource more than obtained in the optimization. As a result, we highlighted the scenario where a reduction in cycle time stood out, in which one extra unit was added in the second machine group, representing a 7.41% reduction in cycle time.

Key words: Arena. Mini-fab. OptQuest. Reentrant model. Semiconductor manufacturing process.

Resumo

O escopo deste trabalho foi a simulação da manufatura de semicondutores utilizando o *software* Arena®, com subsequente otimização e análise de sensibilidade do modelo. O processo é considerado extremamente complexo dada a quantidade de etapas, parâmetros de máquina e características altamente reentrantes, as quais tornam a estabilidade do processo de produção difícil de ser atingida. O modelo de produção utilizado foi o Intel Five-Machine Six-Step Mini-fab desenvolvido por Karl Kempf (1994). Foi programado no Arena® e otimizado com o OptQuest®, um *add-on*. Concluímos que a variação no número de máquinas e operadores refletem sobre o tempo de ciclo somente se houver um aumento de uma unidade de recurso a mais do que a obtida na otimização. Como resultado, salientamos o cenário em que uma redução no tempo de ciclo destacou-se e na qual uma unidade extra foi adicionada no segundo grupo de máquinas, representando uma redução de 7,41% no tempo de ciclo.

Palavras-chave: Arena. Mini-Fab. OptQuest. Modelo reentrante. Processo de manufatura de semicondutores.

1 Introduction

A factor that highly contributes to the stability of a production process is the accuracy of cycle time (ANKENMAN et al., 2007), which is equivalent to stating that honoring the commitment of product delivery to the client within the predicted time enhances the chances of a sustainable business. In this sense, the study of cycle time, which is the period between the arrival of raw material and the disposal of final goods, is essential to keep the service at a high level of quality (MCNEILL et al., 2005).

Li (2007) and Vogt (2003) argue that the semiconductor manufacturing process is undoubtedly the most complex in existence. Planning this environment may be considered as a challenge (JANG et al., 2013).

Semiconductors are high-tech components used in almost every modern electronic device, which explains the rapid growth of this industry (EL-KHOULY et al., 2011).

In a real scenario, opportunities for tests and simulations involving the whole supply chain are rare, which highlights the importance of simulation. The semiconductor production process can be analyzed using a discrete model, which is considered advantageous for simulation, as it reflects the reality accurately: all data collection is discrete and can be solved by a number of distinct models (HE et al., 2011).

According to Tsakalis et al. (1997), the complexity of semiconductor manufacturing lies in the great variety of machinery required, the high number of production steps, and its highly reentrant features. The reentrancy feature allows a product to be processed by the same tool group more than once and that processing variables might differ from one moment to the next. Lot size and processing time are some of these variables. In semiconductors manufacturing, reentrancy is necessary due to the production of different layers of circuits to compose an integrated circuit (RAMIREZ-HERNANDEZ, 2009).

According to Mello and Ferreira (2014), planning of production processes usually does not consider the application of alternative machines or composition between different machines. These authors state that the use of a single machine in the manufacturing process can result in a process bottleneck but that the inclusion of alternate machines can be used as a strategy to avoid bottlenecks.

The aim of this article is to develop a study to measure the sensitivity of cycle time to other variables of the system, such as number of machines and operators available, using a simulation model of a complex discrete manufacturing process in Arena® in order to identify and analyze the potential variables to be minimized. The semiconductor manufacturing model was developed by Karl Kempf (1996), with support by Intel in partnership with the University of Arizona (TSAKALIS et al., 1997). The system models a semiconductor factory with reentrant characteristics, meaning that the products may be processed more than once by the same tool group without a linear flow in the manufacturing environment.

With the purpose of optimizing the production, Wisniewski and Rymaszewski (2013) suggest a generic model to be simulated in Arena® and concluded through a sensitivity analysis. This is financially advantageous because it allows analyzing each parameter in the system before acquiring or employing resources.

The use of software is usually indicated when there is a need to optimize a specific process in order to increase its efficiency (PRADELLA, 2013).

Oliveira et al. (2013), in an analogous application, applied Arena® software in a study in which they proposed using value stream analysis in an existing production process for the inclusion of a new product and identifying bottlenecks. The authors performed the production process simulation, sensitivity analysis, and optimization.

2 Methodology

This is a quantitative modeling study, aimed at understanding the impact of preset control variables on performance variables in a specific domain. More specifically, it is normative, qualitative, and axiomatic, because it delves into the development of a strategy for optimizing the objective function (MIGUEL et al., 2010), which, in this case, is the cycle time.

2.1 The model

The Mini-fab model is rich in details in order to add variability and uncertainty to the simulations. The model is complex, consisting of five machines, seven process steps, batching, set-ups, and reentrant features that makes a product use a single tool twice, in addition to the arrival and departure of two different products in the system (TSAKALIS et al., 1997).

The model used in this study and its equipment sets is named Intel Five-Machine Six Step Mini-Fab, which was initially developed by Karl Kempf (1994) for the semiconductor industry. In this model, two products, named X and Y, are considered. Products X and Y start arriving at the beginning of the simulation at time zero. Products X and Y have inter-arrival times following an exponential distribution with a mean time of 200 and 330 minutes, respectively.

The machines are modeled into three tool groups (1, 2 and 3). Each tool group is composed of two identical machines. Tool group 3 is an exception, because it is composed of a single machine, adding up to a total of five machines in the system. In each of the three tool groups, named TG1, TG2, and TG3, there is one operator available for loading and unloading. The TG1 refers to a diffusion-like batching semiconductor manufacturing. In this tool group, the machine can run if three appropriate lots are available to load at the same time. In TG2, a lithography-like process, the machine can run as soon as a lot is available, and it is likely that other lots will arrive before the first lot finishes processing. TG3 refers to the implantation process, where it can be running either on product or a test wafer lot.

The loading and unloading times of the process are shown in Table 1 (KEMPF, 1994).

Table 1: Loading and unloading times in minutes for each tool group

Tool group	Loading (min)	Unloading (min)
1	20	40
2	15	15
3	10	10

Source: Kempf (1994).

The reentrant features of the model can be explained by the multi-process steps set. As shown in Figure 1, the first step consists of products flowing from the arrival station to TG1. After that, they are sent to TG2, then TG3, then TG2, then TG1, then TG3, from where they are disposed. For each step, the processing time is shown in Table 2.

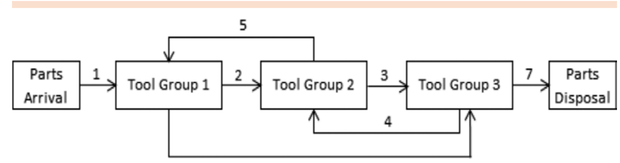

Figure 1: Process steps
Source: Adapted from Kempf (1994).

Table 2: Processing time, in minutes, for each step

Process step	Processing time (min)
1	225
2	30
3	55
4	50
5	255
6	10

Source: Kempf (1994).

All five machines presented in the model require 30-minute preventive maintenance every 12 hours. The machine in TG3 requires both preventive and emergency maintenance. The emergency maintenance is such that the machine uptime follows the uniform function UNIF(24,76) hours methodology and machine downtime follows the UNIF(6,8) hours methodology.

The processed products in TG1 are batched in groups of three. If it is the first time the product is being processed by TG1 (step 1), the batching process does not take into account the type of part. Otherwise, the products are grouped by their types.

The last feature that should be mentioned is that the machine in TG3 requires setup according to process step number and product type. If two sequential processed products are directed to different processing steps, a 10-minute set-up is required. If two sequential processed products are of different types, but waiting for the same processing step, a 5-minute set-up is required. If two sequential processed products are directed for different steps and different types, a 12-minute set-up is required.

Kempf (1994) suggests three operators for the whole system. Two of them work 540 minutes per shift, of which 6 minutes are for breaks and 60 minutes for meetings and daily training. The last operator, a maintenance technician, works 600 minutes per shift, of which 45 minutes are for breaks and 30 minutes for meetings and daily trainings.

2.2 The simulation

In this section the aim is to make clear how the model features were programmed in Arena®. The model can be divided into five parts: arrival, TG1, TG2, TG3, and departure. Figure 2 shows the arrival of parts as it happens in Arena®. Figures 3, 4, and 5 show TG1, TG2, and TG3, respectively.

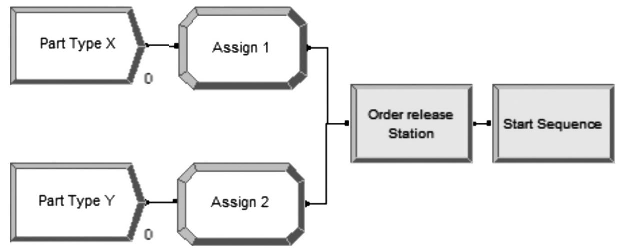

Figure 2: Arrival of Products
Source: Arena®.

Two Create modules are used to create products X and Y. Two Assign modules are used to assign values to four attributes: Entity, Sequence, Arrival Time, and Entity Type.

One Station block is used to inform Arena® that the current product is at that location (KELTON et al., 2010). A Route module starts the sequence, defined in Sequence function, available at the Advanced Transfer panel.

A Station module starts the process. The units are batched in groups of three, of the same type or not, depending on the process step. The process follows: loading machine, machine process, and unloading machine.

The units are unbatched and a Route model defines the next Tool Group that should process each part.

From a Station module, the products are loaded, processed and unloaded. The Route module defines the next station to which each product should go.

Starting again from a Station module, a Decision module is used to compare process step and type of the next product to process, and step and type of the last product processed. If necessary, the setup process follows.

The Assign blocks before the Process Modules are there to assign specific values to two variables, Products Setup and Step.

Next, products are loaded, processed, unloaded, and forwarded to the next station according to the sequence set. After being processed

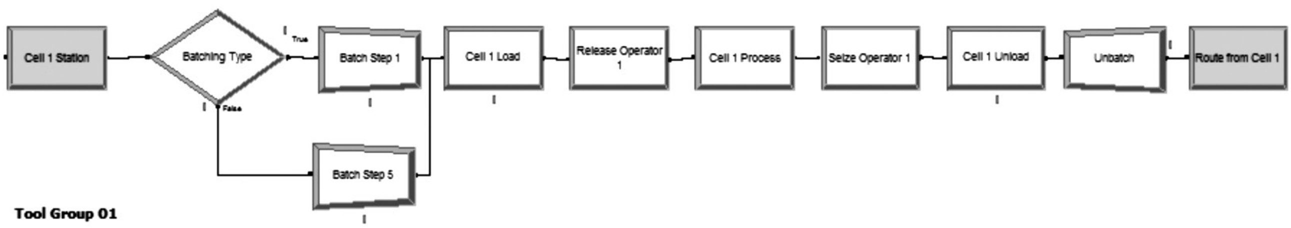

Figure 3: Tool Group 1
Source: Arena®.

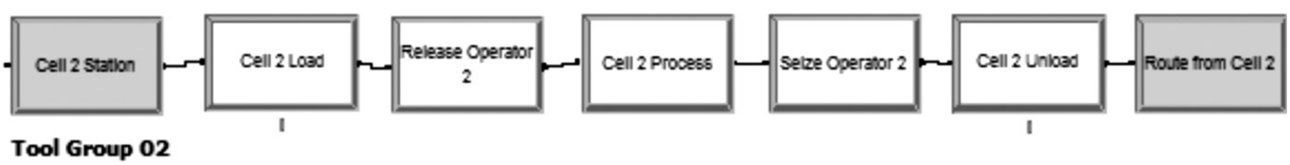

Figure 4: Tool Group 2
Source: Arena®.

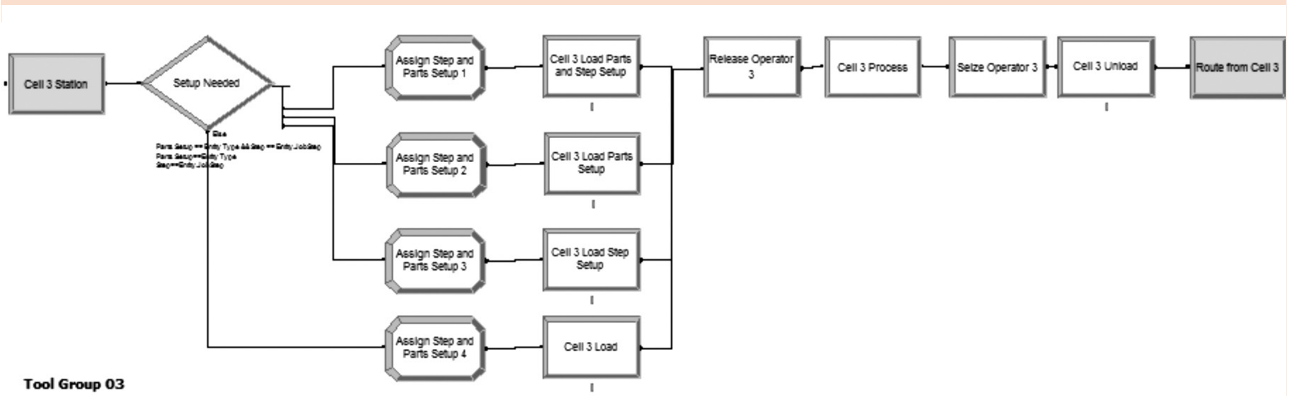

Figure 5: Tool Group 3
Source: Arena®.

twice for each Tool Group, the products are disposed, as shown in Figure 6.

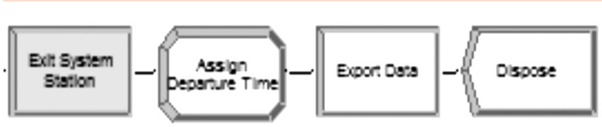

Figure 6: Disposal
Source: Arena®.

The Assign block assigns values to Departure Time and Cycle Time.

As a result of the simulation, a text file is generated to allow some analysis with output data. This file contains four columns, each one with an attribute value, as shown in the table below.

Table 3: Values in the text file

Attribute	Column #
Replication Number	1
Arrival Time	2
Cycle Time	3
Entity Type	4

Source: Adapted from Arena®.

Arena's® capabilities include the development of an animation of the simulation in order to facilitates the understanding of the system and check its perfect running. An image of the animation was captured and is presented in Figure 7.

2.3 Optimization

To obtain the optimal solution and the sensitivity analysis, a specific tool called OptQuest®, provided by Arena®, was used. OptQuest® is an application that enhances the analytical capabilities of Arena®, making it able to identify the best solution for the model simulated since the user provides the min and max for various resources (ROCKWELL AUTOMATION, 2013).

The software, developed by Rockwell®, is greatly used in academic research that seeks ideal scenarios in the most diverse fields. The sensitivity analysis was developed such that two parameters were varied for six scenarios. The parameters were the number of machines and operators available in each tool group. Each of the six scenarios were subdivided into three parts, each with the maximum limit of one unit more than the previous one, adding up to eighteen scenarios to be analyzed.

Control variables, response variables, constraints, and the objective function were defined in OptQuest® to generate the optimal solution: minimizing the cycle time. The iteration time for the model was also defined before running it.

A time of 240 hours was considered for each iteration, which is equivalent to thirty days, eight hours per day.

Control variables are parameters that can be varied on an interval defined by the user and are the resources of the model that are involved in the process of optimization. In this case, the number of machines and the number of operators in each tool group were defined as control variables. In mathematical terms, these parameters are denominated decision variables (KELTON et al., 2010).

Two constraints for the optimization were defined as well. The first states that the sum of the machines in all tool groups must be between five and eight; the second, that the sum of operators in the system must be between three and eight.

The response variable to compose the objective function was defined to be the average total time cycle of products X, Y and of both, generating three different scenarios. A briefing is shown in Table 4.

For the sensitivity analysis, the intervals for control variables were varied three times; each one added one unit from the maximum limit. This way, it is possible to analyze how much the number of machines and operators influence the cycle time.

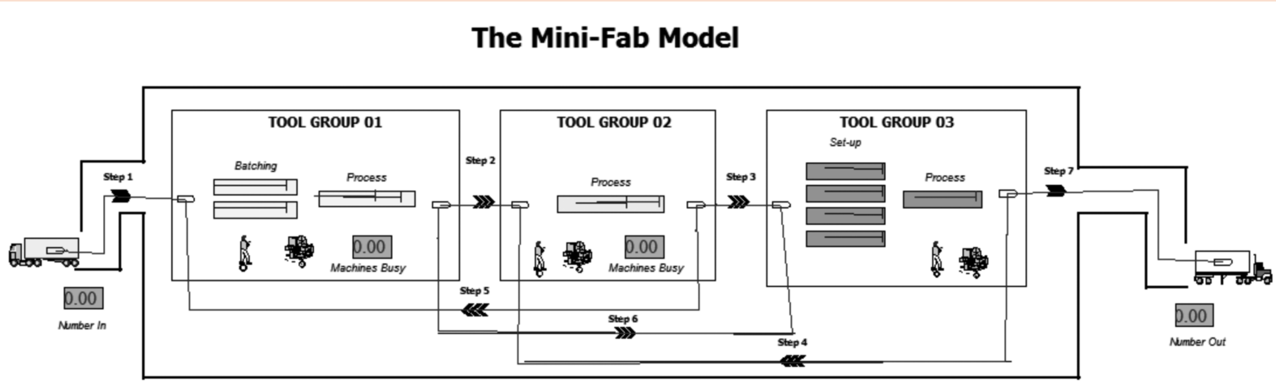

Figure 7: Animation
Source: Arena®.

Table 4: Parameters for the optimization

Parameters	
Control variables and its intervals	2 ≤ # machines TG1 ≤ 3
	1 ≤ # machines TG2 ≤ 2
	2 ≤ # machines TG3 ≤ 3
	1 ≤ # operators TG1 ≤ 2
	1 ≤ # operators TG2 ≤ 2
	1 ≤ # operators TG3 ≤ 2
Constraints	3 ≤ (# machines TG1) + (# machines TG2) + (# machines TG3) ≤ 8
	3 ≤ (#operators TG1) + (#operators TG2) + (#operators TG3) ≤ 8
Response Variables	Total time of products X and Y in the system.
Objective function	Minimize the sum of the average total time in the system of products X and Y.

Source: The authors.

The scenarios studied were based on the optimization parameters already mentioned, varying only the max interval of each variable one at a time. Table 5 shows the modified constraint for each scenario.

3 Results

The results of optimization given by OptQuest® are shown in Table 6. It is relevant to notice that the optimal iteration number is presented with the total number of iterations run by the software.

The optimization results of the eighteen scenarios for the sensitivity analysis are presented in the Tables 7, 8, and 9.

Even though the number of optimal iterations varies in each scenario, it is clear that the objective function value remains the same in each group of scenarios, from one to six, as well as the values of cycle time for products X and Y. It is possible to elaborate a summary of the results, shown in Table 10.

Table 5: Sensitivity analysis scenarios

Scenario	Modified constraint from optimization scenario
Scenario 1.1:	2 ≤ # machines TG1 ≤ 4
Scenario 1.2:	2 ≤ # machines TG1 ≤ 5
Scenario 1.3:	2 ≤ # machines TG1 ≤ 6
Scenario 2.1:	1 ≤ # machines TG2 ≤ 3
Scenario 2.2:	1 ≤ # machines TG2 ≤ 4
Scenario 2.3:	1 ≤ # machines TG2 ≤ 5
Scenario 3.1:	2 ≤ # machines TG3 ≤ 4
Scenario 3.2:	2 ≤ # machines TG3 ≤ 5
Scenario 3.3:	2 ≤ # machines TG3 ≤ 6
Scenario 4.1:	1 ≤ # operators TG1 ≤ 3
Scenario 4.2:	1 ≤ # operators TG1 ≤ 4
Scenario 4.3:	1 ≤ # operators TG1 ≤ 5
Scenario 5.1:	1 ≤ # operators TG2 ≤ 3
Scenario 5.2:	1 ≤ # operators TG2 ≤ 4
Scenario 5.3:	1 ≤ # operators TG2 ≤ 5
Scenario 6.1:	1 ≤ # operators TG3 ≤ 3
Scenario 6.2:	1 ≤ # operators TG3 ≤ 4
Scenario 6.3:	1 ≤ # operators TG3 ≤ 5

Source: The authors.

Table 6: Optimization results

	Results
# Optimal Iteration	13/64
Objective Function (min)	X: 1437.20
	Y: 1542.60
	X+Y: 2979.80
# machines TG1	3
# machines TG2	2
# machines TG3	3
# operators TG1	2
# operators TG2	1
# operators TG3	2

Source: The authors.

Having the sum of the cycle time for products X and Y obtained by the optimization as a reference, the percentage reduction of the cycle time for each scenario can be calculated, as shown in Table 11.

Table 7: Simulation results for scenarios 1.1, 1.2, and 1.3 (with, respectively, 4, 5, and 6 as the maximum number of machines available in TG1) and 2.1, 2.2, and 2.3 (with, respectively, 3, 4, and 5 as the maximum number of machines available in TG2)

Results	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 2.1	Scenario 2.2	Scenario 2.3
# Optimal Iteration	18/88	15/96	15/87	59/88	33/89	56/96
Objective Function (min)						
X:	1343.53	1343.53	1343.53	1298.76	1298.76	1298.76
Y:	1538.48	1538.48	1538.48	1475.76	1475.76	1475.76
X+Y:	2882.01	2882.01	2882.01	2774.13	2774.13	2774.13
# machines TG1	4	4	4	3	3	3
# machines TG2	2	2	2	3	3	3
# machines TG3	2	2	2	2	2	2
# operators TG1	2	2	2	1	1	1
# operators TG2	2	2	2	2	2	2
# operators TG3	2	2	2	2	2	2

Source: The authors.

Table 8: Simulation results for scenarios 3.1, 3.2 and 3.3 (with, respectively, 4, 5, and 6 as the maximum number of machines available in TG3) and for scenarios 4.1, 4.2 and 4.3 (with, respectively, in 3, 4, and 5 as the maximum number of operators available in TG1)

Results	Scenario 3.1	Scenario 3.2	Scenario 3.3	Scenario 4.1	Scenario 4.2	Scenario 4.3
# Optimal Iteration	21/88	17/96	17/96	mar/88	3/106	mar/93
Objective Function (min)						
X:	1437.20	1437.20	1437.20	1437.20	1437.20	1437.20
Y:	1542.60	1542.60	1542.60	1542.60	1542.60	1542.60
X+Y:	2979.80	2979.80	2979.80	2878.88	2878.88	2878.88
# machines TG1	3	3	3	3	3	3
# machines TG2	2	2	2	2	2	2
# machines TG3	3	3	3	3	3	3
# operators TG1	2	2	2	3	3	3
# operators TG2	1	1	1	2	2	2
# operators TG3	2	2	2	2	2	2

Source: The authors.

Table 9: Simulation results for scenarios 5.1, 5.2 and 5.3 (with, respectively, 3, 4, and 5 as the maximum number of operators available in TG2) and for scenarios 6.1, 6.2 and 6.3 (with, respectively, 3, 4, and 5 as the maximum number of operators available in TG3)

Results	Scenario 5.1	Scenario 5.2	Scenario 5.3	Scenario 6.1	Scenario 6.2	Scenario 6.3
# Optimal Iteration	18/96	41/107	39/108	37/93	18/111	15/108
Objective Function (min)						
X:	1437.20	1437.20	1437.20	1401.87	1401.87	1401.87
Y:	1542.60	1542.60	1542.60	1498.41	1498.41	1498.41
X+Y:	2979.80	2979.80	2979.80	2900.29	2900.29	2900.29
# machines TG1	3	3	3	3	3	3
# machines TG2	2	2	2	2	2	2
# machines TG3	3	3	3	3	3	3
# operators TG1	2	2	2	1	1	1
# operators TG2	1	1	1	2	2	2
# operators TG3	2	2	2	3	3	3

Source: The authors.

Table 10: Optimization results for all the scenarios

# Optimal Iteration	Optimization	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Objective Function (min)	2979	2882	2774	2979	2878	2979	2900
# machines TG1	3	4	3	3	3	3	3
# machines TG2	2	2	3	2	2	2	2
# machines TG3	3	2	2	3	3	3	3
# operators TG1	1	2	1	2	3	2	1
# operators TG2	2	2	2	1	2	1	2
# operators TG3	3	2	2	2	2	2	3

Source: The authors.

Table 11: Percentage reduction of cycle time

	Objective function (min)	Percentage variation (%)
Optimization	2979	Reference value
Scenario 1	2882	3.39
Scenario 2	2774	7.41
Scenario 3	2979	0
Scenario 4	2878	3.51
Scenario 5	2979	0
Scenario 6	2900	2.74

Source: The authors.

4 Conclusion

From the optimization model, it is possible to conclude that for the initial scenario, the sum of the cycle time of products X and Y is 2979.80 minutes, considering tool groups TG1 and TG3 with two machines each, and TG2 with only one, and two operators for TG1 and TG3, and one operator for TG2.

From the sensitivity analysis, comparing each subdivided scenario, we notice that the possibility of one extra unit of resource is not advantageous, because after the first unit is acquired there is no reduction in the cycle time.

Among the studied variables, the bottleneck of the simulated factory is the number of machines available in TG2. This is proved by the fact that the increase in one unit of this resource reduces the cycle time in 7.41%, the greatest reduction index, as it can be inferred from the results presented in Table 11.

The best opportunity for resource acquisition in order to reduce cycle time refers to an additional machine in TG2, as the greatest value in Table 11 refers to scenario 2, which is related to number of machines in TG2, as in Table 5. On the other hand, hiring an additional operator for TG2 represents a disadvantage in terms of cycle time, because the value remains the same, as well as the acquisition of an extra machine to compose TG3, which can be inferred by the null terms in Table 11 related to scenarios five and three, respectively.

References

ANKENMAN, B. et al. *Cycle time prediction for semiconductor manufacturing via simulation on demand*. Illinois: Northwestern University, 2007.

EL-KHOULY, I. A.; EL-KILANY, K. S.; EL-SAYED, A. E. Effective scheduling of semiconductor manufacturing using simulation. *World Academy of Science, Engineering and Technology*, v.5, n.7, p. 211-230, 2011.

HE, F.; DONG, M.; YANG, D. Modeling and analysis of reentrant manufacturing systems: micro and macroperspectives, mathematical problems in engineering. *Mathematical Problems in Engineering*. v. 2011, Article ID 139896, 17 p., 2011.

JANG, H. et al. A model predictive control approach for fab-wide scheduling in semiconductor manufacturing facilities. In: INTERNATIONAL CONFERENCE ON MANAGEMENT AND CONTROL OF PRODUCTION AND LOGISTICS, 6., Fortaleza, Brasil. *Proceedings*... Fortaleza: IFAC, 2013.

KELTON, W. D.; SADOWSKI, R. P.; SWETS, N. B. *Simulation with Arena*. 5. ed. Boston, MA: McGraw-Hill, 2010.

KEMPF, K. G. *Intel five-machine six step mini-fab description*. 1994. Available at: <http://aar.faculty.asu.edu/research/intel/papers/fabspec.html>.

KEMPF, K. G. Simulating Semiconductor Manufacturing Systems: Successes, Failures and Deep Questions. In: WINTER SIMULATION CONFERENCE, MANUFACTURING SYSTEMS, INTEL CORPORATION, 1996, Coronado, California. *Proceedings*... Coronado, California: IEEE, 1996.

LI, W. *Comparison of simulation-based schedule generation methodologies for semiconductor manufacturing*. Arkansas: Department of Industrial Engineering, University of Arkansas, 2007.

MCNEILL, J. E. et al. Cycle-time quantile estimation in manufacturing systems employing dispatching rules. In: WINTER SIMULATION CONFERENCE, 2005, Orlando. *Proceedings*... Orlando, Florida: IEEE, 2005.

MELLO, M. H.; FERREIRA, J. C. E. Avaliação de presença de recursos alternativos em plano de processos para melhorar o desempenho de sistemas manufatura. *Revista Produção Online*, Florianópolis, v. 14, n. 2, p. 648-678, abr./jun. 2014.

MIGUEL, P. A. C. et al. *Metodologia de pesquisa em engenharia de produção e gestão de operações*. Rio de Janeiro: Elsevier, 2010.

OLIVEIRA, R. B. M.; CORRÊA, V. A.; NUNES, L. E. N. P. Uso da simulação computacional com o mapeamento do fluxo de valor para auxiliar na tomada de decisão. *Exacta-EP*, São Paulo, v. 11, n. 1, p. 47-57, 2013.

PRADELLA, S. Gestão de processos: uma metodologia redesenhada para a busca de maior eficiência e eficácia organizacional, *Revista Gestão & Tecnologia*, Fundação Pedro Leopoldo, v. 13, n. 2, 2013.

RAMIREZ-HERNANDEZ, J. A. A simulation-based approximate dynamic programming approach for the control of the Intel mini-fab benchmark model. In: WINTER SIMULATION CONFERENCE, Austin, TX, 2009. *Proceedings*..., Austin, TX: IEEE, 2009.

ROCKWELL AUTOMATION. OptQuest for Arena. User's Guide. Rockwell Software. Available at: <http://iiesl.utk.edu/Courses/IE406%20S07/Slides/Arena%20OptQuest%20User's%20Guide.pdf>. Access in: 2013 22 Sep.

TSAKALIS, S. K. et al. Hierarchical Modeling and control for reentrant semiconductor fabrication lines: a Mini-Fab benchmark. In: INTERNATIONAL CONFERENCE ON EMERGING TECHNOLOGIES AND FACTORY ANIMATION, 6., p. 508-513, 1997, Los Angeles. *Proceedings*... Los Angeles: IEEE, 1997.

VOGT, H. Discrete-event simulation using SystemC: interactive semiconductor factory modeling with FabSim. In: SIMULATION CONFERENCE, Diusbrug, Germany, v. *Proceedings*... Duisburg: IEEE, 2003.

WISNIEWSKI, T.; RYMASZEWSKI, S. The use of simulation and genetic algorithm with different genetic operators to optimize manufacturing system. West Pomeranian University of Technology, Szczecin, Department of Information Systems Engineering, *ACS Applied Computer Science*, v. 9, n. 1, 2013.

Recebido em 11 ago. 2015 / aprovado em 30 set. 2015

Para referenciar este texto
VALENTE, S. A. et al. Optimization of a semiconductor manufacturing process using a reentrant model. *Exacta – EP*, São Paulo, v. 13, n. 2, p. 275-284, 2015.