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# VALIDATION AND VERIFICATION OF THE SIMULATION MODEL OF A PHOTOLITHOGRAPHY PROCESS IN SEMICONDUCTOR MANUFACTURING

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## ABSTRACT

Simulation modeling provides an effective and powerful approach for capturing and analyzing complex manufacturing systems. More and more decisions are based on computer generated data derived from simulation. The strength of these decisions is a direct function of the validity of this data. Thus the need for efficient and objective methods to verify and validate simulation models is greater than ever. The validation of a simulation is generally acknowledged as an integral part of a simulation project. But in a vast majority of the reported applications of simulation, there is no mention of verification and validation.

In this paper, the issue of formal verification and validation of a semiconductor manufacturing simulation model is addressed. A simulation model of the photo area of the clean room of Cirent Semiconductor in Orlando, Florida was built. Various approaches for verification and validation were applied and a valid semiconductor manufacturing simulation model was developed.

## 1 INTRODUCTION

Semiconductor Fabrication is a business of high capital investment and fast changing nature. To be competitive, the production in a fab needs to be effectively planned and scheduled starting from the ramping up phase, so that the business goals such as on-time delivery, high output volume and effective use of capital intensive equipment can be achieved. Simulation provides an effective tool for defining the path from competitive concepts to real world solutions.

Cirent Semiconductor, in Orlando, a manufacturer of Application Specific Integrated Circuits (ASIC), uses simulation as a decision aid. They have a simulation team who have developed simulation models of the two fabs in Orlando to assist management in making decisions. Work in process (WIP), cycle time (CT), throughput, equipment utilization, and idle time are some of the performance measures that the management would like to optimize. The second fab, OR2, is in the ramp-up phase, and daily changes that are made in the fab have to be reflected in the model to make accurate decisions. More attention is now being focused on the accuracy of data collected, means for extracting and importing data to the models, and keeping abreast of changes in the fab. The managers and engineers are nowadays rightly concerned about whether the model is a good representation of the fab, and whether the results are correct. This is addressed through verification and validation. The simulation team does validation by comparing the spreadsheet models and fab data, but formal procedures have not been applied for the purpose of validation. The verification and validation procedures are not formally documented either. Also, the management decided to experiment with a new software called Lucent AP. This is a customization of AUTOMOD/-AUTOSCHED, a product of Autosimulations Inc.

The decision was made to build a model of the photo area using the Lucent AP and validate it. The objective was to validate the software, while establishing a framework for validation of simulation models. The photo area was chosen to be modeled because it is the largest area in the fab with the most expensive equipment, the steppers. Each wafer goes through the photo area multiple times. This area was designed to be the bottleneck of the fab, since capacity lost on steppers is equivalent to capacity lost for the whole fab. Moreover, the model would help evaluate process changes, determine maximum capacity, decide on staffing, and perform what-if scenarios with different technologies and routings.

## 2 LITERATURE REVIEW

In one of the earliest papers in the validation literature, Naylor & Finger (1967) gave a 3 step approach for validating a simulation model. The first step is to develop a model with high face validity. The second step is to test the assumptions of the model empirically ensuring conceptual validity. They mention the well known chi-square and Kolmogorv-Smirnov tests for comparing actual frequencies with the theoretical frequencies. Finally, the third step is establishing operational validity which is determining that the models output data has sufficient accuracy for the model's intended purpose.

Hoover & Perry (1984) presented some common approaches to verification and validation. Tracing the simulation, logical relationship checks, and graphics were described as verification techniques. They suggested validation methods such as Turing tests (see Turing, 1950), extreme behavior tests, and statistical techniques.

Sargent (1984 a, 1984 b), discussed the two major attributes of operational validity: (1) whether the problem entity (system) being modeled is observable or not and (2) whether subjective or objective approaches are used in determining the model's operational validity. There are major statistical procedures used with observable entities in operational validity, such as statistical hypothesis tests, confidence intervals, and graphical comparison of output data (see for example Balci, 1994; Balci & Sargent, 1984; Sargent, 1984 a, b).

Balci & Sargent (1984) presented univariate and multivariate approaches to construct the model range of accuracy, which is the joint confidence region of the confidence intervals (CIs). In approach I, univariate techniques and Bonferroni inequality are used to develop simultaneous confidence intervals. In approach II, multivariate statistical techniques are used to develop simultaneous confidence interval (sci) or joint confidence regions (jcr). A methodology for validation is also presented which allows the use of different types of statistical procedures and provides for a trade off analysis among sample sizes, confidence levels, sizes of confidence intervals, and if desired cost of data collection. In another paper, Balci & Sargent (1982) illustrate a procedure for using Hotellinge 2 -Sample $T^2$ test to test the validity with respect to the mean behavior of a multivariate response simulation model that represents an observable system. Some remedial measures are given to satisfy the assumptions underlying the 2-Sample $T^2$ test, namely independence, multivariate normality, and equality of variance-covariance matrix.

Kleijnen has contributed significantly to the field of validation. In Kleijnen (1995 a), he surveyed verification and validation of simulation models. For verification, he discussed modular programming, checking intermediate simulation output through tracing and graphics. For validation, he discussed obtaining real-world data, comparing simulated and real data through graphs, Schruben-Turing tests, *t* tests, and testing whether simulated and real responses are positively correlated and moreover have the same mean. He also suggested using a new statistical procedures based on regression analysis and sensitivity analysis based on design of experiments and regression analysis. Through a case study, Kleijnen (1995 b) performed sensitivity analysis to determine whether the model inputs have effects on the model outputs that agree with expert's intuition, when there is no data available on the real system. In Kleijnen et. al. (1996), he recommended a simple statistical test that uses regression analysis in a novel way for the validation of trace driven models. This test concerns a (joint) null hypothesis: the outputs of the simulated and real systems have the same means and the same variances. Technically the differences between the simulated and real outputs are regressed on their sums, and the resulting slope and intercept are tested to be zero.

Sargent (1996a) summarized the entire validation process with a step by step procedure supported by techniques that can be used in each step. Conceptual model validity, verification, operational validity, and data validity were discussed. He suggests using boxplots, histograms and behavior graphs as subjective methods for validation.

A survey of current simulation model verification, validation , and testing (VV&T) techniques and how they can be applied throughout the life cycle of a simulation study is given by Balci (1994). He stresses the importance of the life cycle application of VV&T for successful completion of complex and large scale simulation studies.

It is evident from the above discussion that validation is an integral part of simulation model right from input data collection through model development to output data analysis. Integration of verification and validation with model development is crucial. The goal of this study is to develop a valid simulation model of the photo area of a wafer fabrication facility and to establish a framework for validation of the simulation model at Cirent Semiconductor.

## 3 DEVELOPMENT OF SIMULATION MODEL

During the wafer fabrication process, the lots go through the photo process several times. Each time requires a different pattern and after each photo step other processes such as implant or plasma etch will occur. The model includes labor and its availability with shifts. Note that this fab is in the ramping stage and the model was built for a certain period in the ramp. The model has to be updated, i.e., the routings, equipment and labor should be added as the changes occur in the fab. This model is used to study the impact of the operating policies on the cycle times, throughput, WIP (work in process ) levels, queue times, and utilizations of the photo area. The photo area is expected to be the bottleneck since each wafer goes through it multiple times.

The simulation model was developed using the Lucent AP simulation software. This model was built using a collection of input files grouped according to four categories:

- Factory Resources
- Products

- Demand - Starts, WIP
- Operating Rules

The factory resources include the equipment, labor and calendars for the various resources. Products defines the parts being manufactured and the process flows (routings) for each part. The starts define the number of lots to be released and the frequency in which they have to be released. Operating rules are the task selection rules for stations and operators.

An important aspect of this model is the delays used for the dummy work stations. In order to use the performance measures applicable to the whole fab, the process steps between the photo steps were assigned dummy work stations. Constant delays based on a few weeks average were defined at these work stations.

The model has process flows for two parts - Linear and Zone tester. The process flow is the sequence in which the part travels through the fab. Each main process step is assigned a work station, process time and description, and may further be divided into sub-processes which are called stepalts. Each stepalt is also assigned the same attributes as the main process step. The data available for the process steps is the average from historical data in the database, and engineering estimates. The time and method observation study was done to verify and validate the engineering and historical data estimates. Once the valid model was built, it was verified.

## 4 VERIFICATION OF THE MODEL

The simulation model was verified in a number of ways:

- The computerized representation was checked by people other than the author and the model logic was followed for each event type.
- The state of the simulated system, i.e., the contents of the event list, state variables, statistical counters were printed and compared against hand calculations and fab database. Examination of the utilization of a work station revealed that its utilization was unreasonably low. The error was because this station family had too many stations and was corrected. Another error was discovered when certain process steps showed very high queue times. When investigated it was disclosed that the metric “wait for operator percentage” for the station family assigned to this process step was high. This was in turn because, the number of operators assigned to the specific operator class were less than required.
- The simulation software produced a Gantt chart of the machine and operator activities which were printed and checked for the sequence i.e., load, process, unload, etc. The down events and their frequencies were also verified.
- The software produced a trace file which consists of detailed output representing the step-by-step progress of the simulation model over the simulated time. This allowed detection of subtle errors. The trace file displayed that some stations were included in misspelled station families and were actually excluded from the simulation. Since these stations were not very highly utilized, it did not show up as a capacity constraint. Nevertheless the utilization numbers would have been misleading if this was not corrected.
- The output was checked for reasonableness. Similar runs with different arrival rates were performed to ensure that the throughput and work-in-process levels were different for differing arrival rates. Changing the processing times of process steps or number of machines in station families changed the utilization of the machines and the work-in-process levels. Reasonable output indicated correct logical and structural data assumptions of the model, and thus verified the model.

## 5 VALIDATION OF THE MODEL

Once the model was verified, the next step was validation to determine whether the computerized model was an accurate representation of the system under study. Operational validity is primarily concerned with determining that the model’s output behavior has the accuracy required for the models intended purpose over the domain of its intended applicability (Sargent, 1996b). One of the important requirements of operational validity is that the system being modeled must be observable. In this phase, most of the validation, testing, and evaluation takes place. Some of the techniques we used in validation of the model are discussed below.

- Comparison to other models (Sargent, 1996b; Banks et al., 1988; Balci, 1994)- One of the best ways to validate a simulation model is to compare the results predicted by the model with the performance of the real system and other valid models, such as analytic and spreadsheet models. The output of the simulation model showed conformance with spreadsheet models. The utilization percentages of the station families from the model were checked against spreadsheet calculations and were observed to be very close. The actual values, however, cannot be displayed due to proprietary reasons.
- Extreme condition tests (Sargent, 1996; Banks et al., 1996; Balci, 1994; Law & Kelton, 1991)- This method consists of carrying out runs to simulate extreme situations and to verify that the model performs as intended in such situations. The model was tested to see if it would accommodate unlikely events, for example, when the in-process inventories were zero,

the output was zero. The model was stressed i.e., the workload was increased by increasing the starts beyond the capacity and it behaved as anticipated. The high starts led to very high queue times especially in the steppers and the WIP, and cycle time went overboard. Thus we can say that the model performs correctly in such situations.

- Parameter variability (Sensitivity Analysis) (Sargent, 1996b; Banks et. al, 1996; Kleijnen, 1995 b; Balci, 1994; Law & Kelton, 1991; Carson, 1989)- Sensitivity analysis can be defined as the systematic investigation of the reaction of the model outputs to drastic changes in model inputs. Sensitivity analysis consists of comparing the effect of change in input parameters, indicated by simulation results, to the expected trends. Sensitivity analysis was performed to see if the model behaved as the system would, and to identify the factors that the model was most sensitive to. Increasing the starts gradually showed that after a certain point, the queue times and WIP increased enormously. The sensitivity of the model to the starts was studied using the WIP curves as shown in Figure 1. When starts are increased from 1000 to 1100, the WIP only increases slightly, but when increased to 1250 the model becomes very congested and the WIP increases rapidly. This information was useful in understanding the relationship between the WIP and wafer starts, and documentation of this information is useful in future capacity analysis.

The model parameters such as processing times of the stations were changed and the effect was observed. The model was found to be quite sensitive to the processing times, especially in the case of the steppers. This was helpful since the fab is in the ramping stage, and the stepper engineers can work on improving the process and reducing the times. The model was also found to be sensitive to the inspection process, since it was labor intensive and the operators had to manually perform the process. This was useful since the staffing for the inspection process would be planned more carefully.

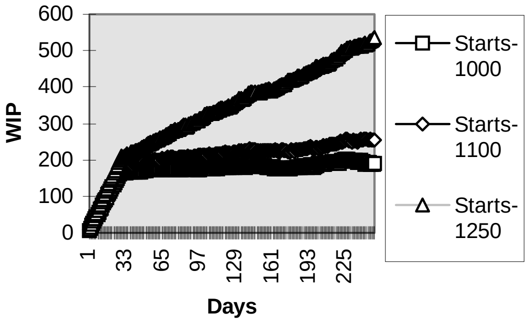



Figure 1. Sensitivity of Model WIP to Starts

- Turing test (Schruben 1980) - In this test, simulation output is presented in the same format as the reports generated from the actual system. Then, a manager or expert in the system is presented with a shuffled collection of genuine and simulated documents. If the person is able to do so then their explanation of how they were able to do so is used to improve the model. Graphs can also be used in the Turing test. In our model, the experts could not differentiate between the two sets and were even surprised at the closeness of the data sets.
- Graphical comparisons using box plots, and histograms (Balci, 1994; Sargent, 1996a)- The data generated from the model for use as a reference distribution is displayed graphically along with the data from the system. These two sets are compared subjectively to determine whether the model has sufficient accuracy for its purpose. The histograms and box plots assume that the data from the model and system are identically distributed. For each performance measure, a histogram of the model data is used as the reference distribution, and compared to the histogram of the system data to aid in deciding whether the model's performance measure has sufficient accuracy for the model's intended purpose. Similarly for each performance measure, a box plot of the model data to be used as a reference, and a box plot of the system data are placed in the same figure to be compared subjectively. A rough guideline in comparing box plots is that if the $25^{th}$ percentile line for one sample exceeds the median line for the other sample, there is strong evidence of a difference between the means.

For our model, histograms of the WIP values were developed from the model and the system as shown in Figures 2 and 3. From these two figures, we observed that the system histogram lies within the reference distribution (model generated distribution), since the model histogram extremes overlap the system histogram extremes. Thus, based on the two figures, the simulation model can be judged to have sufficient accuracy with respect to the average WIP/day.

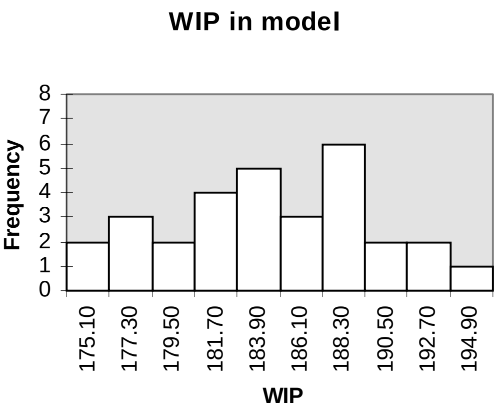



Figure 2. Histogram of  Model WIP Data

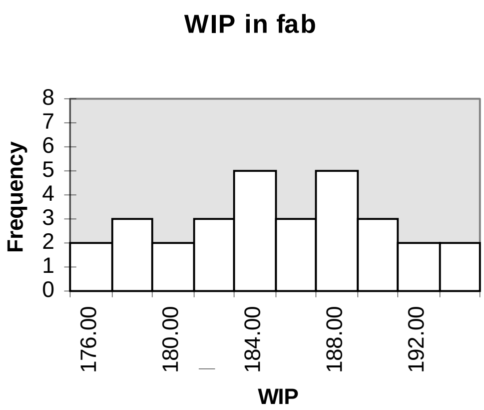
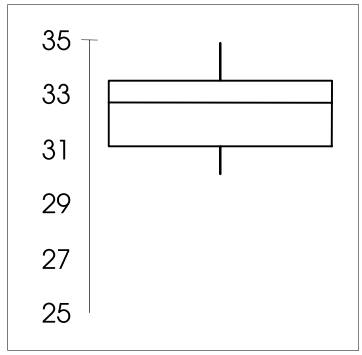
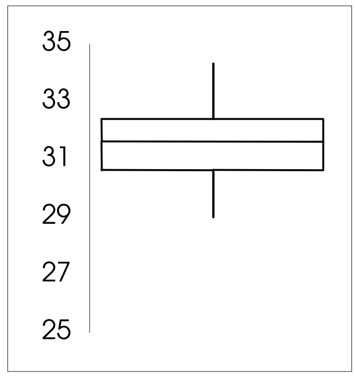



Figure 3. Histogram of Fab WIP data




Model CT box plot




Fab CT box plot

Figure 4. Box Plots of Model and Fab CT

The box plots generated from the model were used as reference plots and comparisons were made between the model and system plots for operational validity. Operational validity was performed to determine if the model's average cycle time (CT) was within the required accuracy.  Figure 4 is the box plot of the model and system data. The two figures were placed adjacent to each other and compared subjectively. From the two box plots, following the rough guideline it was observed that the 25$^{th}$ percentile line for one sample does not exceed the median line of the other and there is no strong evidence of a difference in means. Moreover there is some indication that the model has been more consistent, though the system shows marginally more extreme behavior (i.e., the extreme lines of the system exceed that of the model). This may be due to some special causes and does not come in the way of calling the model operationally valid.  Note that the cycle time values are not shown for proprietary reasons.

The above tests were some of the subjective techniques used to validate the model of the photo process. The results from this process gave the managers more confidence in using the model.  Other statistical test such as the regression test proposed by Kleijnen and the autocorrelation tests are currently being performed for more objective validation.

The process of validation does not stop here and it has to be done throughout the life cycle of the simulation study. Especially since this is a model of the photo area of a fab in the ramping stage, the data and structural assumptions have to be validated as the change occurs in the fab and the model has to revalidated, whenever it is updated.

## 6 CONCLUSIONS

Despite the extensive use of simulation in systems analysis, especially in a complex semiconductor manufacturing facility, many skeptics have reservations concerning its merit.  The engineers and analysts who use the model outputs to aid in making design recommendations and the managers who make decisions based on these recommendations justifiably look upon a model with some degree of skepticism about its validity.

This project focused on validation and verification of a wafer fabrication simulation model. A model of the photo area was developed and subjectively validated by comparing its output to the outputs from spreadsheet models. The equipment utilizations were comparable to the other models and the system. The model passed the Turing test for the CT and WIP data. Extreme behavior and sensitivity tests were also performed. The sensitivity tests showed that the steppers were most sensitive to wafer starts and processing times. Histograms and box plots were also used to establish credibility of the model.

## REFERENCES

Balci, Osman and Sargent, Robert, G., Validation of Multivariate Response Models Using Hotelling's two-sample $T^2$ Test, Simulation, December 1982.

Balci, Osman and Sargent, Robert, G., Validation of Simulation Models via Simultaneous Confidence Intervals, American Journal of Mathematical and Management Sciences, 1984, Vol. 4, Nos. 3 & 4, p. 375-406.

Balci, Osman, Validation, Verification, and Testing Techniques Throughout the Life Cycle of a Simulation Study, Annals of Operations Research, 1994.

Banks, Jerry, Haddock, Jorge, McKay, Kennth N., and Rothenberg, Jeff, Panel Session: Validation: Expanding the boundaries, Proceedings of the 1988 Winter Simulation Conference, p. 402-407

Banks, Jerry, Carson, John, S. and Nelson, Barry, L., Discrete-Event System Simulation, Prentice-Hall International Series, 1996.

Carson, John S., Verification and Validation: A Consultant's Perspective, Proceedings of the 1989 Winter Simulation Conference

Hoover, Stewart V., and Perry, Ronald F., Validation of Simulation Models:The Weak/Missing Link, Proceedings of the 1984 Winter Simulation Conference.

Kleijnen, Jack, P.C., Bettonvil Bert, Groenendahl, Willem, Van, Validation of Trace-Driven Simulation Models: Regression Analysis Revisited, Proceedings of the 1996 Winter Simulation Conference, 1996.

Kleijnen, Jack, P.C., Statistical Validation of Simulation Models, European Journal of Operational Research 87, 1995 a , p.21-34.

Kleijnen, Jack, P.C., Verification and Validation of Simulation Models, European Journal of Operational Research 82, 1995 b , pp.145-162.

Law, Averill, and Kelton, David, Simulation Modeling and Analysis, McGraw-Hill, Inc., 1991.

Sargent, Robert, G., Simulation Model Validation, Simulation and Model Based Methodologies: An Integrated View, Springer-Verlag, 1984a, pp. 537-555.

Sargent, Robert, G., A Tutorial on Validation and Verification of Simulation Models, Proceedings of the 1984 Winter Simulation Conference, pp. 115-121.

Sargent, Robert, G., Some Subjective Validation Methods Using Graphical Displays of Data, Proceedings of the 1996 Winter Simulation Conference, 1996a.

Sargent, Robert, G., Verifying and Validating Simulation Models, Proceedings of the 1996 Winter Simulation Conference, 1996b.

Schruben, Lee W., Establishing the credibility of simulations, Simulation, March 1980.