2004-01-01

Thin-Film Simulation Model for Comparing Production Schedules in a Semiconductor Fabrication Facility

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Recommended Citation
Arisha, A., Young, P.:Thin-Film Simulation Model for Comparing Production Schedules in a Semiconductor Fabrication Facility. FAIM, 2004: International Conference for Flexible Automation and Intelligent Manufacturing,Toronto, Canada, pp 1089 - 1096.

Thin-film Simulation Model for Comparing Production Schedules in a Semiconductor Fabrication Facility

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Abstract

Analysis of advanced manufacturing systems in any manufacturing industry requires certain level of knowledge about the system. Flexible manufacturing cells, in particular, are commonly used in most wafer fabrication to provide the ability to change product without requiring the construction of new manufacturing plant. This level of flexibility comes at a significant capital cost and, in order to achieve the maximum potential of each cell, it is essential to characterize and establish the performance of these cells in detail before a new production plan is implemented. Using state-of-the-art computer simulation and a structured modelling methodology a generic model of flexible manufacturing cells has been developed and used to examine the impact of changing product volumes (ramps), product priority, and maintenance schedules on the toolset performance. The model has been developed and validated using actual production data and found to effectively duplicate the behaviour of the manufacturing installation. Various criteria, e.g. tool utilization & product cycle time, are used to evaluate the response of the cell to the demands made on it by different manufacturing plans. In this way, a plan that maximizes system performance and reduces risk may be achieved.

1. Introduction

Global competition and rapidly changing customer requirements are demanding numerous changes in the manufacturing environment heralding a new industrial era requiring better planning and control techniques, including recognition of the need for decision-making tools and new approaches to the arrangement of manufacturing systems [1]. Semiconductor manufacturing is one of the most complex industries in terms of technology and manufacturing procedure. The variations in product-mix, re-entrant flow, and parallel equipment using different technologies make production scheduling a major challenge. To complicate planning activities further, the flexible manufacturing cells (tools) used in semiconductor manufacturing are extremely expensive and hence it is not possible to experiment with schedules within the facility due to the risk of production loss. There is, therefore, an immense need for effective simulation models of manufacturing systems, characterizing and analyzing the processes that allow the effect of changes in the production environment on the system to be predicted and used to increase utilization and enhance performance.

The process by which very large-scale integrated circuits are manufactured can be divided into four basic steps: wafer fabrication, wafer probe, assembly or packaging, and final testing (Figure 1).

Semiconductor manufacturing facilities face many challenges including capacity planning, product mix, production scheduling, and varying production demand. They are generally composed of an integrated set of flexible manufacturing systems (FMS). Each individual FMS has a set of flexible manufacturing cells that are nominally identical in process and function.

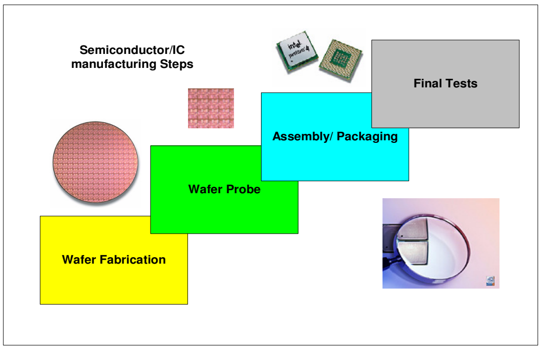

Figure 1:Basic operation sequence for wafer fabrication

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Wafer fabrication is the most technological complex and capital intensive of all four phases [2]. It involves the processing of silicon wafers by building up the layers and patterns of metal and dielectric to produce the required circuitry. The number of operations can be well into the hundreds for a complex component such as a microprocessor. Many of the wafer operations are performed in a clean-room environment to prevent particulate contamination of the wafers. Product moves through the fab in lots, often of a constant size based on standard containers used to transport wafers. The operations may vary widely depending on the product and the technology in use, a simplified diagram to show the main operations in wafer fabrication can be seen in Figure 2.

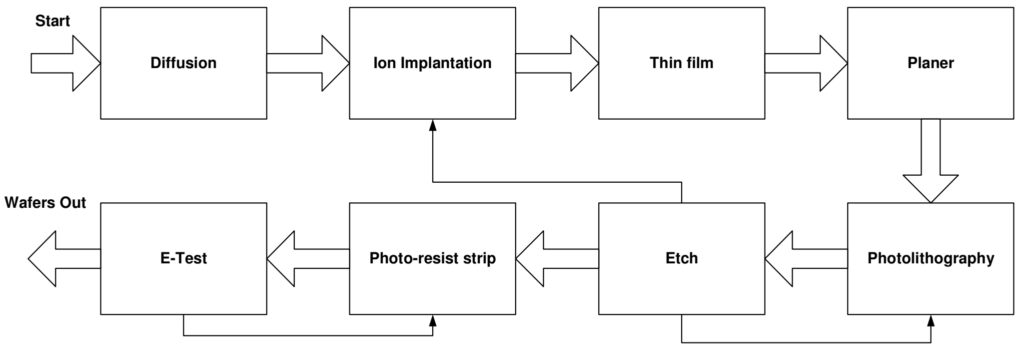

Figure 2: Basic operation sequence for wafer fabrication

Production scheduling of the FMS's in this dynamic environment is a difficult task due to the complex nature of the process itself, reentrant constraint operations, product diversity and resource costs. Conventional approaches for planning have, for the most part, used deterministic models to provide an adequate solution. Uzsoy *et al.* [2] reviewed the complexity and models for scheduling and planning for semiconductor manufacturing in last decade. Advancing this area, Arisha *et al*. [3] developed a methodology for scheduling product through the photolithography area in wafer fabrication facilities. Simulation results presented in a Taguchi experimental design framework offered a robust methodology to gain quick insights into the behavior of selected parameters within flexible manufacturing system environments [4]. This work uses a similar approach to develop a detailed simulation model for thin-film processes and examines the effect of various planning parameters on the process performance. The primary objective of the model is to provide the planning and manufacturing staff with a risk assessment system to evaluate the performance of the thin-film process under different operating conditions.

2. THIN-FILM PROCESS

Thin-film processes are some of the most sensitive and critical processes in wafer fabrication. Thin-film technology combines the properties of specially developed polymers and chip architecture. Ultimately, the result is an organic memory system with manifold advantages: in speed, manufacturability, energy consumption, storage capacity and cost. In the thin-film system, a substrate is coated with extremely thin layers of polymer. The layers in the stack are sandwiched between two sets of crossed electrodes. Each point of intersection represents a memory cell containing one bit of information.

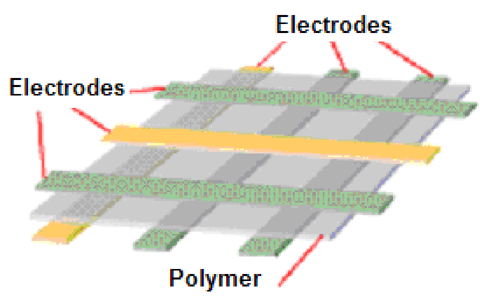

Figure 3: Polymer-Electrodes architecture

To activate this cell structure, a voltage is applied between the top and bottom electrodes, modifying the organic material and different voltage polarities are used to write and read information. In the wafer fabrication, they use sputter tools to build the metal conducting layers and deposition tools to build the non conducting layers. These two processes form the thin-films on the surface of the wafer resulting in a raised surface topography. For accuracy, the surface of the wafer must then be planarised before the next layer can be added.

One of the key challenges in scheduling thin-film production is that the lots go through different manufacturing areas (processes) in a particular order based on the specific product technical configurations. Generating the right schedule requires consideration of the unique operational and resource constraints of each process. The operational constraints may vary from planning regulations (i.e. batch size, order priority, number of parallel tools, availability, etc.) to technological constraints (i.e. process flow, processing times). To generate accurate and executable schedules, all these constraints have to be taken into account simultaneously making the scheduling of lots through the workstations an extremely difficult task. Hence, the ability to predict the performance to the toolset issue under various production schedules is crucial for the planners. There is a need to have a tool that can verify the production plan and analyze its impact on the manufacturing floor before commitment. Here a discrete event driven stochastic model is used to simulate the actual manufacturing system, providing this information in a cost-effective fashion.

3. Simulation Model Objectives

The goal of this work is to develop a re-usable 'generic' simulation model of the thin-film toolset in order to evaluate the following:

- Provide the manufacturing and planning staff with an accurate decision support tool to analyze and characterize the thin-film area.
- Understand the impact of changes to the equipment on the performance indicators.
- Show the effect of scheduled maintenance and unscheduled breakdowns on the overall performance.
- Determine the average utilization of process equipment.
- Find delays and average waiting time.
- Examine different production scenarios.
- Improve cycle time.
- Make recommendations to reduce process variability and enhance performance.
- Provide capacity planning and operation managers with a robust decision support system that mimics the actual shop floor.

4. Modeling Phase

Efficient modeling is the key to ensuring the success of any simulation project, as it is one of the critical tasks in simulation model building [1]. Semiconductor manufacturing in particular needs special requirements in modeling due to:

- complexity
- large amount of data
- reentrant nature
- rapid changes in product configurations due to demand
- manual intervention in the system

These factors make the systems analysis phase more difficult but they reinforce the need for a tool to enable systems modeling. GIGO – garbage in, garbage out – not only applies to data, it applies to the logic of the software and the implementation of a system.

Detailed information on the product, process, and the manufacturing procedure was gathered with the help of manufacturing, industrial and process engineers. The information included, but was not limited to, equipment setup times, equipment loading and unloading times, processing times for every product on every machine, scheduled maintenance, history of unscheduled breakdowns and availability of equipment. Information on the each tools capabilities with regard to each product and layer were also included. This information was essentially used to model and simulate the shop floor of the thin-film process, and is stored in a database attached to the model.

In order to make effective use of simulation in manufacturing systems, it is often helpful to develop a simple, intuitive model that describes the subsystem elements and the relationships among the elements in the simulation model. This project has used a new schematic approach for simulation modeling (SASM) and aims not only to visualize problems or to gain an understanding of complex systems on a heuristic basis, but also to allow the non-specialist to translate the model into coded simulation model. SASM allows the user to understand the information flow with a preliminary perception of the nature of the system that can be used as a starting point for simulation. In other words, a simulation expert who does not know about the manufacturing system will be able to code the simulation model and explore all the interactivities of the system to provide further information and insights (Figure 4).

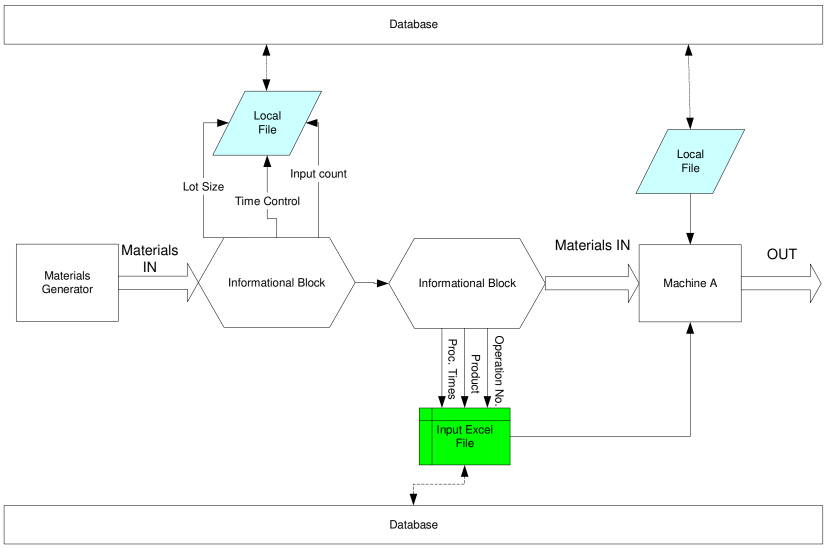

Figure 4: Sample of SASM Diagram

In addition a block diagram (Figure 5) and IDEF0 have been used to model the manufacturing activities within the shop floor. The model flowchart can be simply expressed as:

- Lots come into the Thin-film process according to arrival rates and queue in front of the manufacturing area.
- Machine selection process is function of multiple criteria
  - Preventive maintenance status
  - Unscheduled maintenance
  - Machine status (idle/busy)
  - Lot waiting time
  - Lot priority
  - Set up time (if needed)
  - Processing time of layer
- Lots leaving a machine go to another area for further processing and may either leave the system or return Thin-film for processing of the next layer.

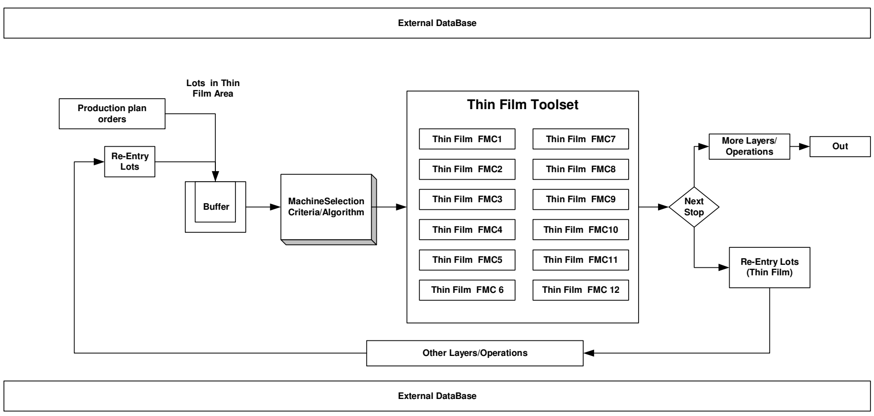

Figure 5: Thin-film model main blocks

5. SIMULATION ANALYSIS

The simulation model was built using the EXTEND simulation software package [5]. The facility is represented by a hierarchical structure; each block represents a separate work center. Operators and transfers between the stations are not modeled. The model shown in the paper is set to 12 flexible manufacturing cells within the thin-film area and comprises a combination of more than 200 unique process steps.

The model allows the user to shut some tools down at the beginning of the production to examine a smaller facility. To simplify the model, some process and inspection steps were combined. The model assumes frequency distributions of unscheduled downtime (i.e. MTBF and TTR) based on the historical data provided by the industrial partner. The extra time spent by staff to get familiar with the tools and production recipes (Learn Rate) has been considered in the model. Figure 6 shows a simple diagram of major model inputs and outputs.

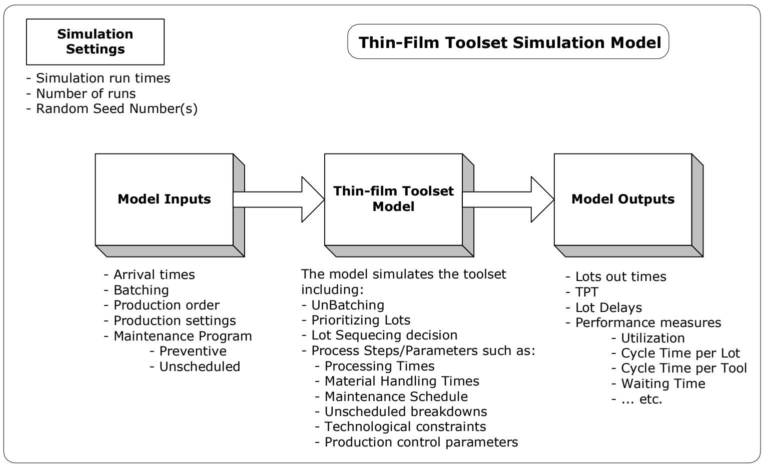

Figure 6: Simulation model inputs/outputs

5.1 SIMULATION ASSUMPTIONS

A number of assumptions were made during the development of the model. These include the following:

1. Every lot has a fixed number of wafers.
2. Learn rate was assumed to be 1 (if not entered).
3. The time between the completion of an operation at the toolset and its return to the toolset for next operation or layer (Operation Delay) was assumed to have a normal distribution with a predetermined mean and standard deviation based on the factory data.
4. Preventive Maintenance (PM) is performed according to the following schedule [6]:
   - Every 168 hours (week) a maintenance of '*x*' hours.
   - The start of PM cycle varies from tool to tool based on information from maintenance engineers.
5. Unscheduled breakdowns occur with an exponential distribution (mean of 'x' hours) and repair time has a normal distribution with a mean of 'y' hours and standard deviation 'z'.
6. The wafers arrive to the toolset in lots according to an exponential distribution with mean 'm' that represents the inter arrival times of the lots.

5.2 VALIDATION AND VERIFICATION PHASE

The strength of decisions made based on the simulation model is direct function of the validity of this data [9], hence the need for efficient and objective methods to verify and validate the model. The verification and validation of the model took place as a continuing process [8] using three approaches.

The first compares the output of the simulation model with actual data from the manufacturing floor and to the output from other pre-existing models. The simulation model output shows a comprehensive trend on cycle time criterion, as shown in Figure 7, and the gap between simulation output to actual shop floor data is about 4%.

The second approach tends to check the output through a trace file, which consists of detailed output representing the step-by-step progress of the simulation model over the simulated time. In addition a decomposition approach (i.e. verification of each fundamental simulation block) was applied. This approach was efficient for debugging purpose and ensured that every block functioned as it should. Moreover, this allows detection of subtle errors.

Finally, the third approach is based on reasonableness of the model outputs. This approach uses independent experts and manufacturing staff, as they are the reference to validate the model results on reasonableness.

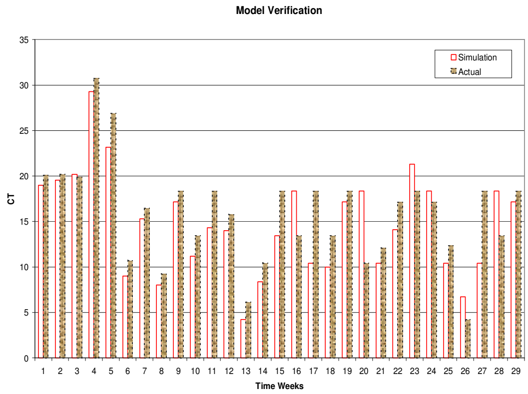

Figure 7: The model verification using actual floor data

6. EXPERIMENTATION

The scenarios were designed to determine the effect of process control parameters/policies on both the average, and the coefficient of variation, of the toolset cycle time and the throughput time within thin-film area. Four ramp profiles with up to twelve tools (machines) subject to eight different products, five different layers, two breakdown scenarios, and two levels of lot priority were tested (Table 1).

Table 1: Experimental conditions for the factors

Factor (Parameter)	Number of Levels	Levels	Factor (Parameter)	Number of Levels	Levels
Ramp Profile	3	Profile 1	Product-mix	2	3 Products
		Profile 2			5 Products
		Profile 3			8 Products
		Profile 4	Priority(Hot Lots)	2	On
Tool Availability	3	8 Tools			Off
		10 Tools	Breakdowns (Unscheduled)	2	MTTF (168,15) MTTR (20,1)
		12 Tools			Off

6.1 REPLICATIONS

The simulation models normally produce the same results on different executions if the default seeds are used for the various streams of random numbers. Hence, there is a statistical approach 'method of replication' has been used to construct a confidence interval for the simulation outputs [7]. For a 95% confidence interval, the number of suggested replications was 12 experiments and hence the simulation experiments were conducted under this condition. The system is started empty and idle and a single run is made to collect '*x*' lots. The model also provides an animation feature to allow the user to track the results as they are generated.

6.2 RESULTS

A host of simulation output measures, as used by production staff to characterize the performance of the thin-film area, were calculated. These included: toolset throughput time, toolset cycle time, tool cycle time, WIP inventory level, tool utilization, utilization versus availability per tool, average waiting time per lot, and more. The different production ramp profiles used during the simulation experiment phase are shown in Figure 8 below.

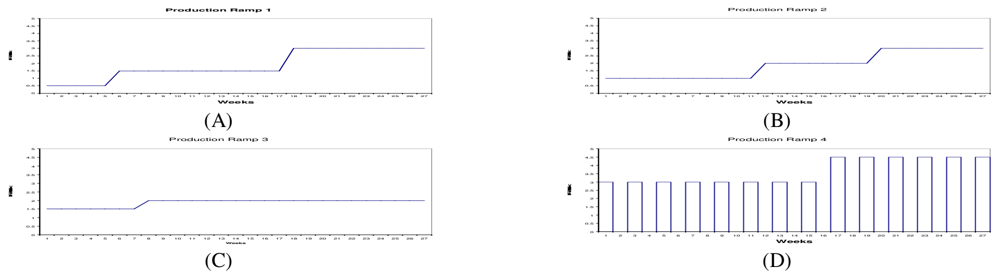

Figure 8: Sample ramp profiles

A. VARIATION IN WEEKLY WIP INVENTORY

Simulation sensitivity analyses were performed to monitor the WIP inventory. The objective of this analysis was to determine the average number of lots waiting to be assigned to a tool. Simulation runs were performed with the different ramp profiles to provide the planner with an idea about the WIP expected in front of the toolset. A sample of the results is shown in Figure 9. The model could also provide the planning and manufacturing staffs with more detailed information about the average waiting time.

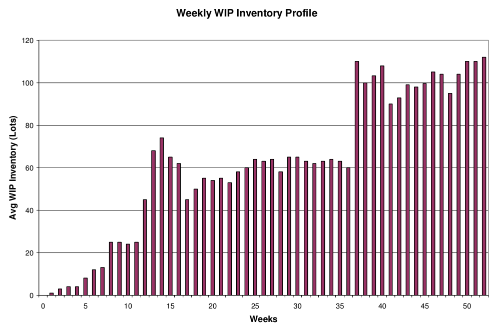

Figure 9: Variation in weekly WIP inventory

B. VARIATION IN CYCLE TIME

The impact of changing the ramp profile on the process cycle time was also examined. The objective here was to show the variability of cycle time within the manufacturing toolset. The effect of increasing the production ramp was clearly seen in the simulation results. Figure 10 shows one of the outputs where it can be seen that the cycle time dramatically increases each time the demand is increased. In particular, these results give an indication of the relationship between the increase in demand and the rise in the CT.

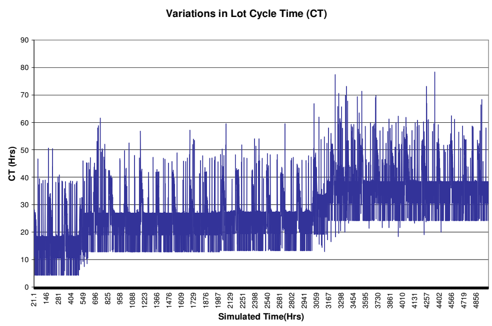

Figure 10: Variability in lot cycle time

C. UTILIZATION VERSUS AVAILABILITY

One of the most important factors for the planners in mass production systems is the availability versus the actual utilization of the equipment. The simulation model provides a comprehensive diagram, Figure 11, showing the availability versus the average utilization per week against the ramp profile. The variation of equipment utilization identifies the weeks in which the tools were over- or under-utilized. This diagram allows the selection of the ramp profile that achieves the best utilization of the toolset while meeting production demands.

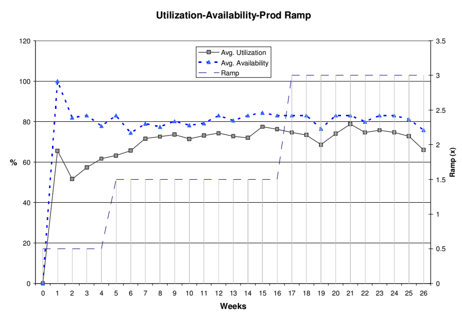

Figure 11: Utilization versus Availability

D. VARIATION IN THROUGHPUT TIME (TPT)

Experiments were designed to analyze the throughput time for lots in the thin-film manufacturing area. The objective here was to compare the effects of each ramp profile on the average TPT within thin-film. Figure 12 shows a significant variation on TPT, and this must be considered when selecting the most appropriate ramp profile.

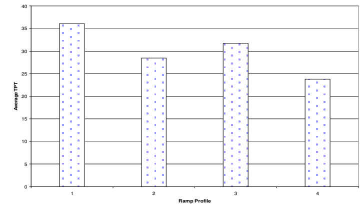

Figure 12: Variation in average TPT

7. CONCLUSIONS

To enhance the solution of planning problems within thin-film process, the simulation model was developed and used to examine the impact of changing planning/process parameters; e.g. product mix and production ramps on toolset performance. The performance measures used to assess the impact of parameter changes are cycle time, average equipment utilization, and the amount of work-in-progress stored in local input buffers. This model has provided a quick efficient decision support tool to examine the impact of any given planning strategies on operating conditions with a reliability that has led to its application on a worldwide basis throughout the organization.

Before the development of this model, the performance analysis of an existing or planned toolset was usually achieved by means of deterministic spreadsheets. Unfortunately, such means ignore critical world phenomena such as system variability and hence model the toolsets as shadows of the real systems. The outputs of these models were thus inaccurate and often overly optimistic.

The simulation model for thin-film toolset developed here is easy to use, efficient, fast and generic. The model has been verified and validated using actual production data and found to effectively duplicate the behavior of the real manufacturing system before being used for parameter studies. The model has been used by the manufacturing and planning staff and resulted a significant reduction in time needed to evaluate the impact of new production plans on the toolset performance.

ACKNOWLEDGEMENT

This research was supported by Intel-Ireland. We would like to thank *Mr. Michael O'Dwyer* (Intel-Ireland), *Mr. Liam Gannon* (Intel-Ireland), and *Prof. James Ignizio* (Intel-US) for their extensive help during the project.

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