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Implementation of Modeling and Simulation in Semiconductor Wafer Fabrication with Time Constraints Between Wet Etch and Furnace Operations

by Wolfgang Scholl and Joerg Domaschke, Infineon Technologies

Abstract: In semiconductor wafer fabrication, time constraints between process steps in furnace and wet etch make it difficult to achieve cycle time targets and maximize machine utilization. For capacity planning, it is difficult to estimate the impact of these time constraints on the machine capacity.

Infineon Technologies Dresden has conducted a study, using discrete event simulation, to investigate the actual situation in the factory and to identify recommendations to eliminate or to reduce the impact of time constraints. The work in this paper yields a 2-day reduction in total cycle time after implementation of findings in the factory.

I. INTRODUCTION

Semiconductor wafer fabrication is perhaps the most complex of modern manufacturing and a branch of industry with a very high investment demand. The cost of equipment is, according to the National Technology Roadmap for Semiconductors, approaching 90% of the factory capital costs.

More than 100 machines are in the production areas of wet chemistry and hot processes at Infineon Technology's Dresden factory. Each

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Dr. Scott Mason will also be holding a Factory Explorer tutorial on Sunday afternoon, December 10, 2000. Please contact WWK (info@wwk.com) or WSC for more information on attending this free tutorial.

tools costs between 0.5 and 2 Million US$. To operate the factory profitably, high machine utilization is a major focus. On the other hand, the factory has to achieve short cycle times to guarantee delivery dates, to enable short learning cycles for new products, to prevent high inventories of materials and to keep the production line flexible. Planning capacity in such an environment with constantly changing conditions is complicated. From this point of view different product mixes, low volume products, hot lots and, above all, time constraints generate a lot of problems for the shop floor control. This is especially true in areas with batch tools, like furnaces and wet benches.

We have found only one reference that describes the specific problem of time bound sequence for semiconductor manufacturing. Robinson and Giglio [1999] developed an approximation based on M/M/c queuing formulas to predict the probability of reprocessing when lots exceed the time limit. Machine characteristics like batch tools, machine failures and different arrival rates were not considered.

In this paper, we analyzed the effects of time constraints between wet and furnace processes on cycle time and utilization. In the first part, a detailed definition of time bound sequence is given followed by a description of the observed problems in the factory.

In the second part, the effects of time constraints are analyzed by using discrete event simulation. At the end, conclusions and recommendations for the planning and the operating are presented and results after implementation are shown. All analyses were focused on a high-volume product planned to ramp up in the next months. We expected the most dramatic problems related to cycle time violations and additional needed investment to achieve the planned capacity targets.

II. PURPOSE OF THE WORK

Time windows between special wet etch and furnace operations are installed by technology development engineers to prevent native oxidation or contamination effects on the wafer surface. For example, a strong dependence between the formation of undesirable interfaces between conductive layers and the waiting time after the wet etch processes were observed. This leads to contact failures, low and unstable yields. Such problems are difficult to discover during wafer processing, and to run a special inline-monitoring would be a large effort. Therefore, as a precaution, short time windows were installed on all critical sequences with typical times of 1, 4 or 8 hours. In many cases, rework is not allowed. Lots with violations of the recommended time-windows have to be scrapped.

Production people had to accept these conditions and to adjust their planning and logistics to meet these time limits. Some manufacturers or factories avoid the problem by dedicating wet tools to each process group that requires a previous cleaning or etch step. The obvious disadvantage of this strategy is the higher demand from wet tools, which leads to higher investment, more clean room space and ultimately to lower capital efficiency.

To limit the number of needed wet benches, our the strategy was to group all machines in one area. This strategy creates a higher demand on the shop floor control, as described in the next section.

Figure 1 shows a simplified time window system between two process steps. The furnace process must start within this window after completing the wet etch process. Normally the machines have to process a mix of different material flows—flows with different time windows and flows with no time limitations. In addition to that, wet etch benches and furnaces are both batch tools, but with different maximum batch sizes.

III. PREVIOUS HANDLING OF TIME CONSTRAINTS

A simple example will show the need of special logistics for time-constrained processes.

Usually the process times of batch furnaces are in the range of four to seven hours. For a work center with three furnaces and a process time of six hours, one furnace (on average) will be unloaded every two hours. In the case of continuous material flow, the mean waiting time of the lots in front of the furnaces will be one hour and the maximum waiting time will be two hours. This means, even before considering down

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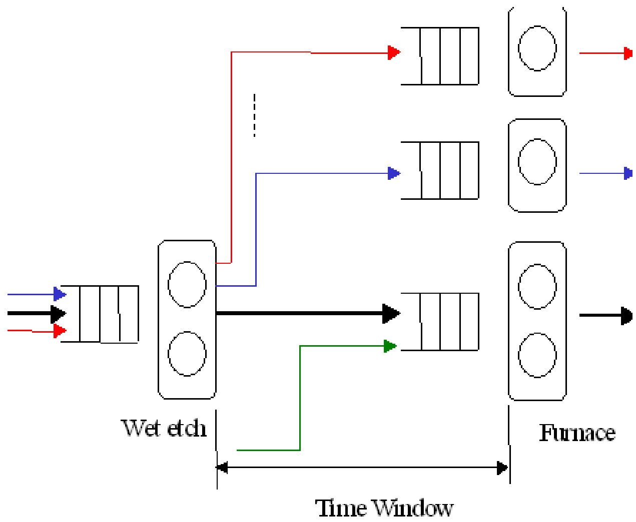


Figure 1: An example of Time Window

events, waiting time to collect a full batch and other usual variability, it would be impossible to meet a recommended one-hour time window.

To guarantee the start of the furnace process within the prescribed time window, a special lot order system and special dispatch rules to control the material flow were introduced to the production process. The basic idea is to collect lots for a full furnace batch (normally six lots) in front of the wet etch bench and to begin processing the batch based on the machine states of the furnaces.

Figure 2 shows a typical example in a factory where a wet etch bench has to process one 1-hour and three 8-hour time constrained flows. Several non-time constrained flows are also at the furnaces.

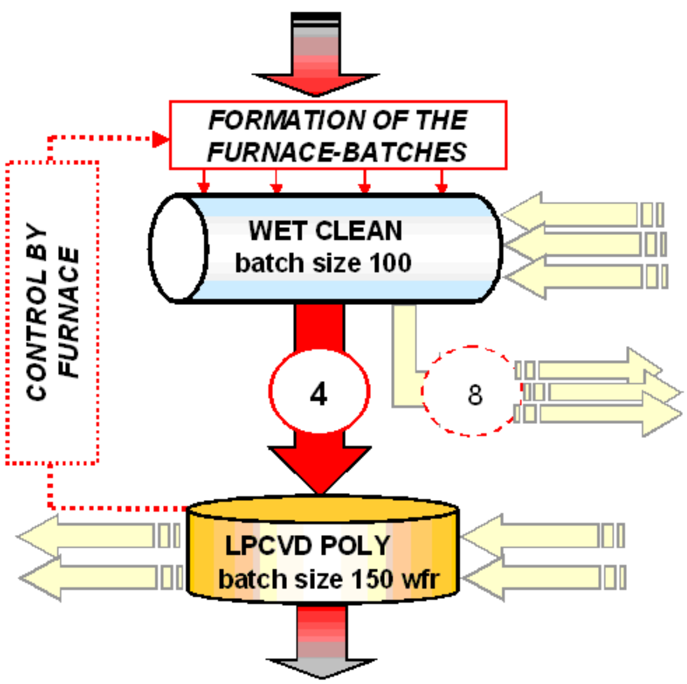


Figure 2: Different material flows on a time constrained system

The maximum time for batch collecting is limited by special rules to avoid an endless expansion of the waiting time. Therefore, it is possible to process batches of a smaller size if additional material is not expected to arrive. The lot-order system is modified in consideration of the relationship between the time window to the furnace process time and the number of tools in the affected tool group.

The following cases were considered in the factory:

A. Very small time-windows compared to the furnace process time (one hour)

B. Time-windows in the range of the furnace process time (four hours or longer)

Case A, a one-hour time-window in front of a long (six hours or more) furnace process, is most critical for the lot order system—especially at highly utilized tool groups. The process for a batch on the wet bench will be started only when the furnace is available (the previous furnace run is unloaded and the wafers are inspected). This is necessary in order to stop the process flow early enough to avoid scrap in case of machine or process problems. This results in a capacity loss because the furnace is idle during the time the wet bench is processing the next batch.

In Case B the risk that one batch will exceed the time window is not so high because it is more likely to find another unloaded furnace during the permitted waiting time when the just-unloaded furnace is down. Here the lots on the wet bench will be started so that they arrive at the furnace just in time when it is unloaded.

In general, time-constrained material flows are prioritized over non-time-constrained flows and special dispatch operators are needed to control them**.**

A. Consequences

In both cases, the wet bench and the furnace are connected to one logistical cluster where all single events, (e.g., down events, standby times or operator availability) have a direct impact on the performance of each single tool.

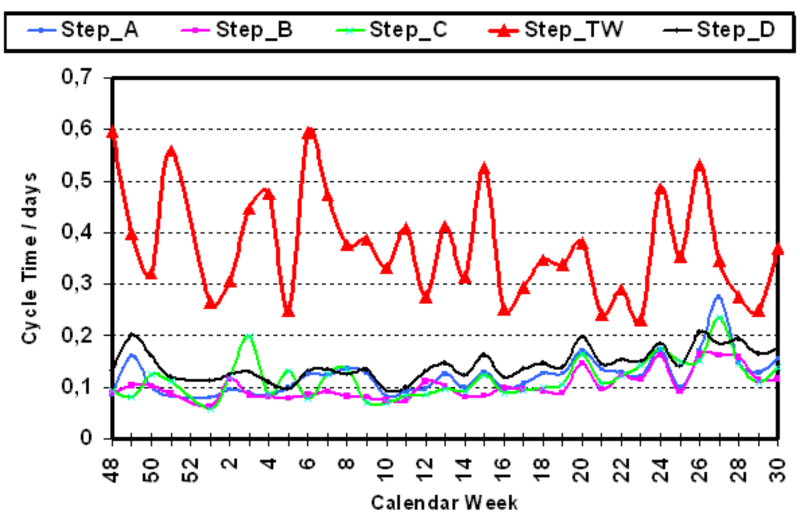


Figure 3: Cycle time behavior of all wet etch processes on one tool group

Figure 3 shows the one tool group's cycle time behavior of five wet etch steps with the same process times. The cycle times of the non-time-constrained process steps "A ... D" are in the planned range. Only the time-constrained process step "TW" shows significant cycle time violations.

Figure 4 shows that the cycle time of the time-constrained wet etch process, Step_TW (WET), correlates to the utilization of the furnace strongly. The special lot order system eliminates the queuing time in front of the furnace, enabling a higher utilization.

The advantages of the order system are as follows:

- The full capacity of the furnaces can be used
- Cycle times of furnace operations are very low due to elimination of waiting times in front of the furnaces.
- The reliability, that lots are started to process within the time window nears 100%

On the other hand, observations in the Dresden wafer fabrication factory show that this strategy causes big cycle time violations against planned values at machines that are not fully utilized. In addition, this order system causes an additional loss in capacity at some of the wet etch benches because of different maximum batch sizes (four lots compared to six lots at the furnace). Furthermore, an additional dispatch operator is needed to control the material flow.

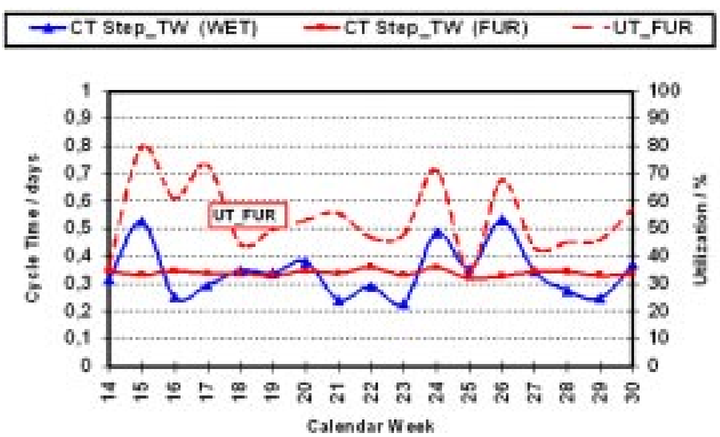


Figure 4: Correlation of cycle time with utilization

IV. MODELING ANALYSIS

The simulation study was conducted by the production department to answer the following questions:

- How can we increase the maximum utilization of the machines with time constraints and still achieve the cycle time targets?

- What should be changed to reach the cycle time targets?

The decision to use discrete event simulation was made because it is one of the most powerful techniques for modeling and analysis of complex processes and systems. In addition to that, people inside the company had experience in simulation analysis.

A. Model description

To prevent unnecessary data collection, verification and validation, single-area models were preferred to a full factory model. This paper presents results of two experiments with different time-bound sequences.

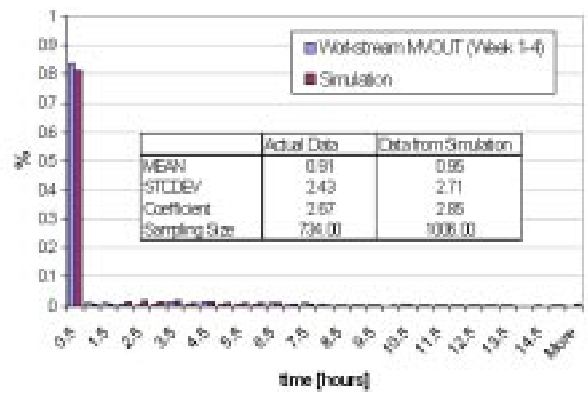
In the first experiment, a furnace group was modeled with a one-hour time constraint. The furnace group includes three machines with a maximum batch size of six lots per machine and the wet etch group consists of two benches, with 2-lot batches. For the single machines, different interruptions were modeled (e.g., mechanical failures and varied preventive maintenance schedules). The model considers arrival rates of nine different products. The time bound sequences were modeled with the basic concept of a Kanban system. For each furnace, six Kanban cards were defined. A lot can only be processed on a wet etch bench after a free card was claimed. A card is occupied until the lot has finished the furnace process.

The second experiment evaluates a furnace group with a four-hour time limit. The model includes six furnaces and four wet etch benches where the handling of these time constraints had some unique attributes (e.g., a maximum batch size of 100 wafers for the wet etch bench and 150 wafers for the furnace). In this scenario, the wet etch machine group had the highest cycle time violation. In contrast to the first experiment, the Kanban cards are released during the furnace process so that the new batch arrives at the furnace before the previous batch is completed. To investigate the behavior of both experiments, a steady state analysis was performed.

B. Data Collection and Data Validation

To analyze the input data from the shop floor, the methods of Operating Curve Management (OCM) were used. OCM is a productivity improvement program at Infineon Technologies that applies queuing theory [Hopp and Spearman, 1996], logistic laws and simulation. Cycle time analysis as a given function of the variability, the capacity, throughput and raw process time stands in the center of this program [Winz et. al. 1999]. For this study, historical records of cycle time by tool groups, equipment utilization, average inventory, and inter-arrival times of the lots were compared against model outputs.

Figure 5 shows that inter-arrival times were verified and validated against actual data of their mean value, standard derivation and coefficient of variance. The results show an average difference of 5%.



	Actual Data	Data from Simulation
MEAN	0.91	0.95
STDEV	2.43	2.71
Coefficient	2.67	2.85
Sampling Size	734.00	1006.00

Figure 5: Inter-arrival rate validation

Figure 6 shows the comparison of actual cycle times vs. simulated output results for a wet etch bench. The actual times are average values over four weeks. With these validation charts, the production people accept that the model is a correct representation of reality.

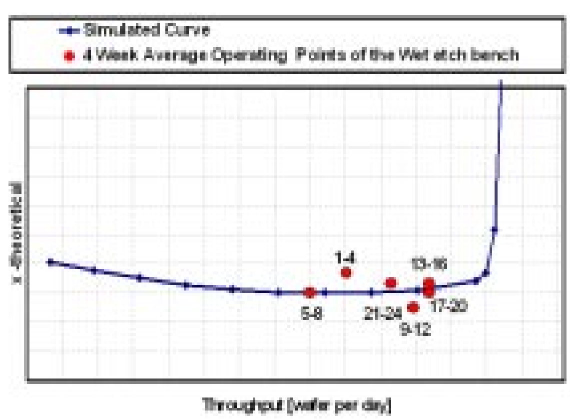


Figure 6: Cycle Time Validation for wet etch

C. Simulation Results and Interpretation

Figure 7 summarizes the relationship between cycle time and throughput from Experiment 1. The curve with a one-hour time constraint clearly shows a loss in capacity of approximately 20% and the steep upward gradient of the curve begins at 85% utilization. This steep portion of the curve is a result of the prioritization of lots with time constraints, and also of high variability at the wet etch benches. Based on these simulation results, a recommendation to eliminate the lot order system is not appropriate. The one-hour time limit compared to the furnace process is too short to allow the lots to arrive independent of the furnace state.

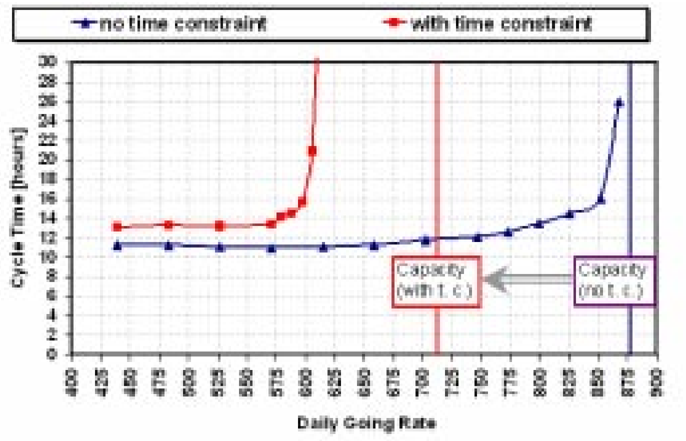


Figure 7: Cycle time vs. Throughput Chart

Simulation results for Experiment 2 show that the order system being used to manage production flow is not required to meet the time windows. Figure 8 shows that with a simple prioritization of time-constrained material flow in front of the furnace and a flexible definition of a minimum batch size, approximately 98% of the lots are within a four-hour window—even with a maximum planned equipment utilization of 85%.

Figure 9 shows the reduction of cycle time for different equipment-utilization levels after eliminating the existing lot order system. The maximum planned uptime utilization is 85% in this case.

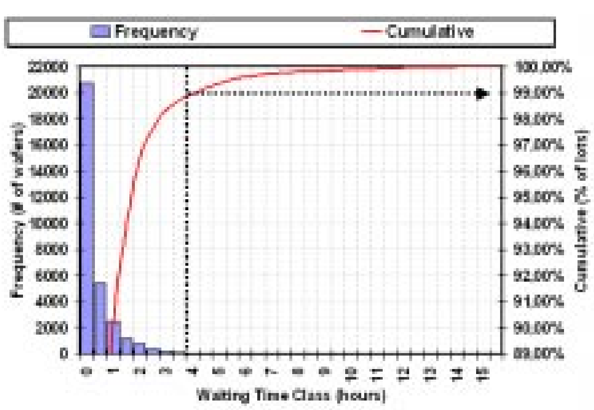


Figure 8: Distribution of the Lot Queue Time

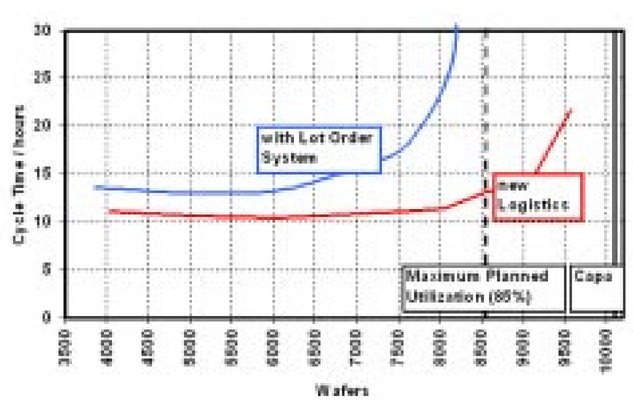


Figure 9: Cycle Time Behavior of a process sequence Wet Etch – LPCVD Poly

V. IMPLEMENTATION OF SIMULATION RESULTS

Based on the simulation results the following changes in the factory were made:

- For time constraints of one to four hours, the maximum planned utilization for furnaces was reduced to 75%.

- For eight-hour time constraints, the lot order system was eliminated. These lots get a higher priority only if they are in the queue of the furnace.

- All existing time constraints were continuously checked, with the intention of eliminating them.

Based on the simulation results it was possible now to force the qualification of new, slightly extended time windows.

After the implementation of the simulation results, the following improvements were seen:

- The logistic system in these areas is simplified; no additional logistic operators are necessary.

- Because wet etch and furnace areas are now managed independently, the batch sizes of the machines can be utilized better. This allows the full planned capacity of the machines to be used.

- The cycle time violations of the wet etch area are eliminated. The total reduction in cycle time in the Dresden factory was two days with the factory loading at that time and more than four days at current wafer starts and product mix.

Figure 10 shows the decrease in actual cycle time in the factory after the implementation of the simulation recommendations.

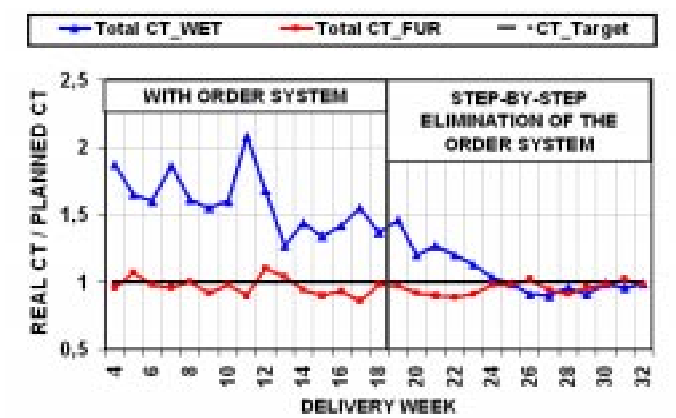


Figure10: Relative cycle time divergence

ACKNOWLEDGMENTS

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Wright Williams & Kelly Releases Freeware for Converting SEMATECH Cost/Resource Model (CRM) Data to Factory Commander™ Format

Wright Williams & Kelly (WWK) has announced the release of a free software program that enables input data from SEMATECH's Cost/Resource Model (CRM) to be converted into WWK's Factory Commander™ format. Factory Commander™, the first commercially available application of its kind, includes all the major functional capability of a cost and resource model for evaluation of financial viability, equipment capacity, product cost, and factory-wide resource requirements. The release of this software allows unsupported CRM users a viable migration path to the next generation, fully supported platform.

"For the first time, users of CRM have a fast and accurate means of translating modeling inputs to a commercially supported application," stated David Lauben, WWK's Program Manager for Factory Commander™. "In the past, any conversion effort of CRM data risked omission or misrepresentation of key modeling aspects. Now entities such as comprehensive tool sets, accurate process routings, detailed labor breakout, and itemized use of process wafers, reticles and low K dielectrics, can be captured and maintained in an environment that has long term training, support, and product enhancements associated with it."

"WWK has a long history of providing continuing support for International SEMATECH's cost and yield modeling research," adds Daren L. Dance, WWK's Vice-President of Technology. "Starting with TWO COOL® cost of ownership software, which was commercialized through a joint SEMATECH/WWK project in 1994, WWK has been pleased to work with International SEMATECH to provide the long-term, world-wide availability that is outside the scope of a consortium with restricted membership."

This software can be obtained free of charge by contacting WWK via email at: support@wwk.com

The software is available to Factory Commander™ users and to all current CRM users with an interest in converting of Factory Commander™.

Benefits of Cost of Ownership

By Daren L. Dance, Wright Williams & Kelly
Previously published at http://www.link2semi.com/articles/word522001.jsp

Historically, purchase decisions have been based on initial purchase and installation costs. However, purchase costs alone do not consider the effects of equipment reliability, utilization, and yield. Over the life of a machine, these factors may have a greater impact on cost of ownership (COO) than initial purchase costs. Lifetime cost of ownership per good device or wafer is generally sensitive to production throughput rates, overall tool reliability, and yield. It is less sensitive to initial equipment purchase price. COO modeling has several benefits for the end user:

- Both suppliers and manufacturers can work from hard data to evaluate process and tool designs.
- The model can provide a clear estimate of the cost of ownership and highlight details that might be overlooked.
- It provides an objective analysis method for evaluating decisions.
- It enables smoother communication between equipment suppliers and users by fostering a common language through the use of similar data sets and cost comparisons that use the same algorithms and equations.
- Equipment suppliers and end users can work together using COO to support an equipment purchase plan.

With a few vital details about purchase, operation, utilization, and performance, users can determine the lifecycle cost of owning a machine or system. However, the underpinnings of a COO model are valid process and tool design data. These are also the data that can be the most challenging to collect.

Data Collection for Cost of Ownership Models

By Daren L. Dance, Wright Williams & Kelly
Previously published at http://www.link2semi.com/articles/word620001.jsp

The largest cost of modeling is data collection. In building a cost model of a machine or process, there are typically four kinds of data[1]:

- The data you want
- The data you need
- The data you get
- The data you don't need but get anyway

Some data are easy to collect: machine and installation, spare parts and consumables, and direct labor costs. Other data are more difficult to collect or more difficult to relate to a specific machine: qualification, training, and process control costs. Still other data depends on how the machine is going to be used: utilization, test, and yield impacts.

The gaps between the data you need and the data you get can be filled in two ways:

- **Published information** - One source of information for a cost of ownership estimate is the example administrative rates published in SEMI E35 COO standard[2]. The Internet is another good source.

- **Sensitivity analysis** - While the exact value for an input may be unknown, often it can be estimated within a certain range for a sensitivity analysis. If the input shows little or no sensitivity to change over the estimated range, then no further validation is needed. If the input does show sensitivity to change, then further data validation is needed. As a minimum, this will show the range of typical COO values for the machine. An example of sensitivity analysis is illustrated in Figure 1.

Valid process and machine design and performance data are most important for a credible COO analysis. While these are difficult data to obtain, using published information and sensitivity analysis will cover much of the gap between the data you need, and the data you get.

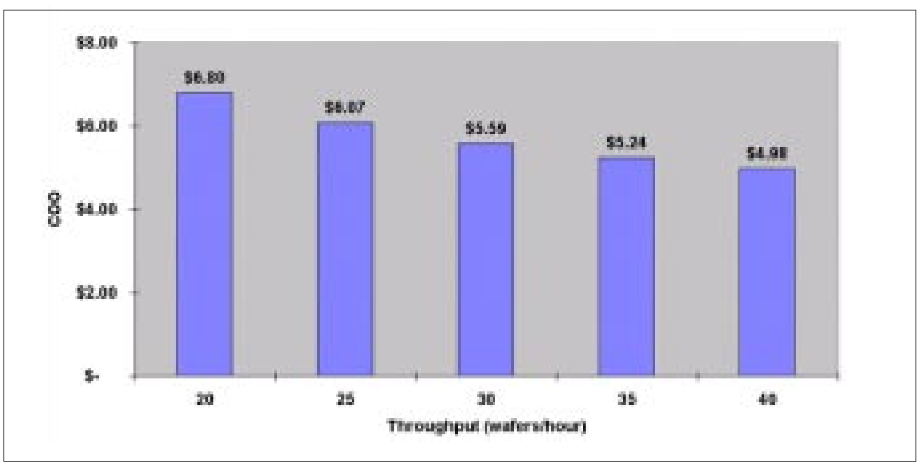

Fig.1 Throughput Sensitivity Analysis

1. F. Chance, J. Robinson, and J. Fowler, Factory Explorer Users' Guide, Wright Williams & Kelly, Pleasanton, CA, 2000, p. 229.
2. Semiconductor Equipment and Materials International, San Jose CA, 2000.

Wright Williams & Kelly Releases FACTORY COMMANDER™ V2.5

Wright Williams & Kelly (WWK) announced today the latest release of its factory level cost and resource evaluation software, Factory Commander™ v2.5. Managers in the semiconductor, flat panel display, solar panel, disk drive, silicon, and other manufacturing and assembly industries use Factory Commander™ to quickly and accurately evaluate their strategic and tactical options.

The new features in this release provide an even greater ability to model a wide variety of real-world situations. Some of the key features include graphical output**,** time-dependent throughput, centralized import/export capability, and removal of tools from inventory.

This release of Factory Commander™ now allows graphical output to be generated without the need for third-party software. Several pre-designed graphs are provided, including a graph of the sensitivity results. Pareto diagrams are available for equipment utilization and material cost. The inputs for throughput capacity are now designed to allow time-varying changes. This enables modeling of processes/equipment where future throughput is expected to improve (or decline). Throughput values can change quarterly for the first two years and annual thereafter. Centralized import/export capability is now provided to facility data transfer from/to spreadsheets for all different data types (process data, equipment data, labor data, etc.). These data types can now be imported from and exported to spreadsheets from one convenient screen enabling faster and more accurate model creation and maintenance.

Some of the other functionality and interface enhancements include:

- Removal of Tools from Inventory. This feature allows individual equipment groups to have their systems eliminated from inventory to allow modeling of a product's ramp-down or the transition between products. Several options are available, each affecting the different aspects of equipment use (production capacity, floor space, depreciation, cash flow, operational cost, etc.).

- 'Recently Used Model' menu. An optional menu window is now provided listing the most recently used models. This feature allows fast and direct access (single click) to previously used models from multiple folder locations.

- Product-to-Product Linkage and Transformation. Products can now be modeled as a series of interrelated sub-products, for instance a front-end product that becomes a back-end product. A transformation quantity can be included that represents an assembly of multiple front-end production units or a division of production units.

- Process Sampling. Rates have been added at the process steps allowing selective production sampling to be modeled. This feature avoids the need to artificially increase the throughput capacity to achieve the correct demand-to-capacity ratio. Rates can also change with time to accommodate planned changes that are anticipated in the future.

- New Reports Added. A new report, Equipment Depreciation over Time, has been added that shows equipment depreciation by group over a quarterly or annual basis. Also, the Unit Cost over Time report has been added showing the cost per good unit out (shipped) over an annual or quarterly basis.

- Descriptive Headers for Exported Report Data. Reports exported to Excel spreadsheets now have a more descriptive header row. The header now includes the units of measure (e.g. k$, %, sq. ft., etc.) and corresponds more closely to the internally generated report.

- Ability to Export Reports to M.S. Word. All calculated reports can now be converted and exported to standard document formats such as M.S. Word (.doc) files or RTF (rich text format) files. This allows model output to be sent to others in the organization without access to, or no knowledge of Factory Commander™.

TWO COOL® v2.5 for Wafer Fab Released

Wright Williams & Kelly (WWK) has announced the release of its latest version of its flagship cost of ownership (COO) and overall equipment efficency (OEE) software, TWO COOL® for Wafer fab. Enhancements included in this software release include: learning curve anlaysis of materials and consumables, conformance to SEMI E79-0200 (OEE standard), expanded sensitivity curve outputs, report on two column model column deltas, and database history tracking. This release is available at no charge to customers covered by warranty and maintenance agreements.

Survey Reveals Widespread Use of Cost of Ownership to Measure Supplier Performance

Dataquest recently surveyed both North American suppliers and users of printed wiring boards (PWBs) to determine the status of this ever-important electronics market. The survey revealed the following:

A full 93 percent of the polled users currently measure supplier performance on a total cost-of-ownership basis, and 97 percent plan on doing so in 2000.*

*source: HDI August 2000, page 14.

Wright Williams & Kelly Forms Strategic Alliance for e-Manufacturing Solutions

Wright Williams & Kelly (WWK) has announced that it has signed a joint services and product development agreement with Five Star Consulting. Under this agreement, Five Star Consulting will provide software and systems development expertise to further enhance and expand WWK's line of productivity and cost management software and services.

Daren Dance, WWK's Vice President of Technology, noted that Scott Pittman of Five Star Consulting will act as WWK's Vice President of Software Engineering to further ensure the seamless integration of both companies' engineering resources. "This agreement provides WWK with additional strengths and expertise as we continue to develop Internet and Intranet based delivery methods for our new e-manufacturing initiatives."

"This agreement further solidifies our long-term relationship with WWK," stated Scott Pittman. "We have worked closely for the past six years on software development projects that have included WWK's TWO COOL® and PRO COOL® cost of ownership simulation software. We are now ready to take the next step in cooperative development strategies."

"This agreement is another important step in continuing our commitment to provide the highest quality products and support for our customers," states David Jimenez, President of WWK. "Scott and Five Star expand our skills in server side delivery vehicles that will allow us to met our customers' near-term requirements for Intranet and Internet based solutions. Additionally, we will be working with Five Star to bring to market their resource scheduling and time management software, further expanding WWK's broad product line in productivity enhancement."