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USING EMULATION TO VALIDATE A CLUSTER TOOL SIMULATION MODEL

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ABSTRACT

Getting the most productivity per square foot of clean room space is a common goal for today's semiconductor fabs. Cluster tool throughput is an important factor in a tool's productivity index. Maximizing and accurately predicting throughput is a high priority in the cluster tool market. This paper presents a flexible and sufficiently accurate cluster tool simulation model. The simulation model can run as an emulator, using the real-world cluster tool scheduler (CTS), or as a stand-alone simulation model using a rule-based scheduler. The process of validating the stand-alone simulation rule-based scheduler against the actual cluster tool scheduler is discussed. A comparison between the two schedulers is detailed. Finally, the results, benefits, and limitations of the simulation model are presented.

1 INTRODUCTION

Cluster tool simulation has been used as a marketing and engineering tool for years. In its simplest form, a cluster tool consists of a main vacuum chamber surrounded by one or more processing modules (PMs), a central vacuum robot, and one or more load locks where the wafer-to-cassette exchange takes place. Silicon wafers follow a route recipe (wafer flow) at the cluster tool. The route recipe defines the step sequence and PM types for wafer processing. The central vacuum robot is used to move wafers to and from the PMs. As wafers are processed in their respective PMs, material is added or the wafer is enhanced in some way.

Simulation case studies have analyzed factors such as wafer-handling options, cluster tool configuration, front-end tool performance, process times and other activities and have evaluated their effects on throughput. These studies have motivated changes in original tool configuration designs, resulting in better throughput performance at less cost than originally anticipated. Tool architectural decisions, such as which vacuum robot to use or the number of PMs needed for a specific recipe, can be easily addressed with simulation. Obviously, the simulation model must accurately predict throughput if sound decisions are to be made.

Cluster tool throughput is limited by either robot or process operations. A tool is process-limited when the robot must sit inactive and wait for the process to finish. For process-limited configurations, throughput predictions can generally be calculated based on the longest processing time. For more complex flows and robot-limited configurations, throughput calculations are more challenging and are very dependent on the cluster tool scheduler (CTS). The CTS is responsible for assigning the substrate move sequence to the vacuum robot in the real-world tool. While the cluster tool is operating, there may be many substrates ready to move at any given time. Selecting the "smart" move that will yield the highest tool throughput is the responsibility of the CTS. Simulation models that attempt to mimic actual cluster tool schedulers will be inaccurate in their throughput predictions if their rule base scheduling algorithms differ from the actual CTS logic.

2 FLEXIBLE CT SIMULATION MODEL

Cluster tools encompass a wide variety of configurations. In addition, there are also a seemingly unlimited number of wafer flows that can process on each cluster tool configuration. Therefore, the simulation model developed by Brooks Automation, AutoSimulations Division, was built as a flexible, data-driven model. Data sets are used to configure and drive the simulation model. A data set consists of seven different input files. These data files define the tool configuration and other model options to be used in the simulation run. Data input includes items such as the number and locations of the PMs, the number of load locks, the robot(s) used, the wafer flow, processing times, and pump and vent times. All of the relative operational parameters of the real-world system are defined through data input. The simulation model reads the data set at the beginning of the simulation run, configures the model both graphically and statistically, and provides the corresponding output. The flexibility of the simulation model includes the ability to:

- Configure the model to use one or two separate vacuum chambers.
- Assign each vacuum chamber as having four, five, six, seven or eight sides (facets).
- Select from 40 different vacuum robots to be used in the respective vacuum chamber(s). These robots include 3 main types: single arm, dual opposing arms, or dual same-side arms.
- Set the robot speeds and other movement parameters.
- Assign up to two PMs per facet, each PM with its own unique attributes such as having a slit valve and processing capacity.
- Define the pump, vent, lift, lower, slit valve open and close, and all other tool timing parameters.
- Define the wafer recipe that includes PM sequence and processing times.
- Define many other graphical and statistical options.

Figure 1 illustrates the simulation model configured as a six-sided cluster tool with four PMs, two load locks, two load ports, a bi-symmetric (dual arm) vacuum robot, and a single arm atmospheric robot.

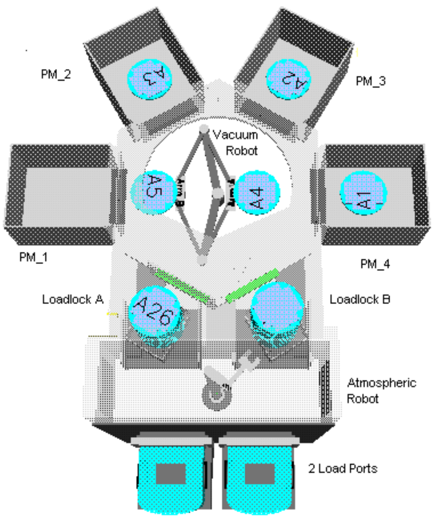

Figure 1: Six-sided Cluster Tool Configuration

The simulation model provides the logic to read in the data set, animate the corresponding tool, operate according to the speeds, sequence, and other inputs; and provides accurate graphical and statistical output.

3 CLUSTER TOOL SCHEDULER

The cluster tool scheduler (CTS) is the actual software used to schedule the wafer move sequence in the real-world cluster tool. Brooks Automation, Inc., Equipment Controls Division, located in Richmond, British Columbia developed the CTS used to validate the simulation model. The CTS is a complex program aimed at optimizing tool throughput for any configuration or wafer flow(s). The CTS is not a rule-based scheduler; it is a search optimization method that is executed before any processing starts. The CTS is fed the tool configuration, and the cassette recipes, along with a specified search depth. The CTS program then uses a branch and bound search algorithm to explore all move possibilities and future resulting moves forward to the specified search depth. Robot move times are supplied as constants and used to predict the arrival and removal times of wafers. The move that initiates the sequence that yields the highest process module utilization within the search horizon is output to the system and the algorithm is repeated. The actual control software will then use the resulting move sequence to schedule PMs and sequence the wafers while the tool is operating.

The use of a predictive scheduler for real-world tool control has two advantages. First, it completely eliminates deadlock situations because routing options that create deadlocks are found and purged during the search. Second, it adapts seamlessly to new recipes and changed conditions. If, at any time during the operation of the tool, the original conditions in which the move sequence was evaluated change, then the move sequence is re-calculated from the current state of the tool. Events that may require the move sequence to be recalculated include events such as a PM randomly going down or the loading of a new cassette.

A higher search depth will result in the evaluation of more moves and resulting future moves, requiring a longer time for the program to execute. However, a higher search depth may provide a more optimal move sequence. For this reason, using the right search depth is important.

4 SIMULATION SCHEDULER

The stand-alone simulation model uses a rule-based scheduler to determine which substrate the robot will move next. The ability exists to program any possible rule-based search algorithm into the simulation model. Since the simulation scheduler is rule based, and the actual CTS scheduler is a search optimization method, a single simulation scheduling rule capable of imitating the CTS for every possible configuration and routing combination is very unlikely. However, careful evaluation of the real-world CTS led to the development of two main scheduling rules that are very close. Only one scheduling rule can be used for a specific simulation run.

4.1 Pull Rule

The first rule can be referred to as a "pull" type rule and is used when the cluster tool has been configured with a single arm vacuum robot. As the name implies, this rule pulls wafers through the system, moving the most downstream wafer first. Obviously, downstream PMs must be empty before the robot can start to move any substrate assigned to process next at that PM. As an example of the pull rule, consider the configuration shown in Figure 2 and a wafer flow of:

`LL->PM1->PM2->PM3->PM4->PM5->LL`

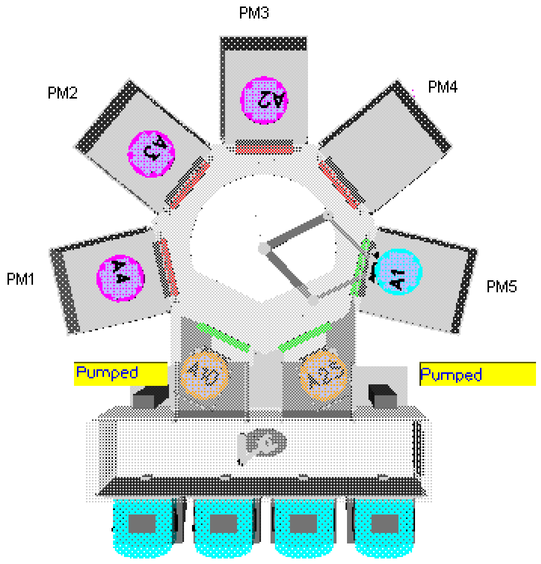

Figure 2: Pull Rule Simulation Scheduler

The single arm vacuum robot is scheduled to move wafer A1 from PM4 to PM5 (as shown), then move the wafer from PM3 to PM4, then move the wafer from PM2 to PM3, etc. The pull rule works the same for all configurations and wafer flow combinations where a single arm vacuum robot is used. Wafers are not eligible to be moved unless they have finished processing in their current PM, and their downstream PM is available and empty. The robot prioritizes wafers based on the number of steps completed and the amount of time a wafer has been waiting to move. This example was simplified to illustrate the pull rule. Transfer limitations, chamber revisits, and other special rules have been included in this algorithm.

4.2 Push Rule

The second rule can be referred to as a "push" type rule and is used when the cluster tool has been configured with a dual arm vacuum robot. As the name implies, this rule pushes wafers through the system using one of the robot arms as a buffer. The robot selects the most upstream wafer first, and then ripples downstream through the move sequence, swapping out wafers as it goes. This rule automatically pre-positions the robot at the "bottleneck" PM, where it waits until a wafer "swap" can be made (providing the configuration is process-limited). The wafer swap consists of replacing the wafer that has just finished processing in the PM with the wafer on the robot buffer arm that has been assigned to process next at the PM. As an example of the pull rule, consider the configuration shown in Figure 3 and a wafer flow of:

`LL->PM1->PM2->PM3->PM4->PM5->LL`

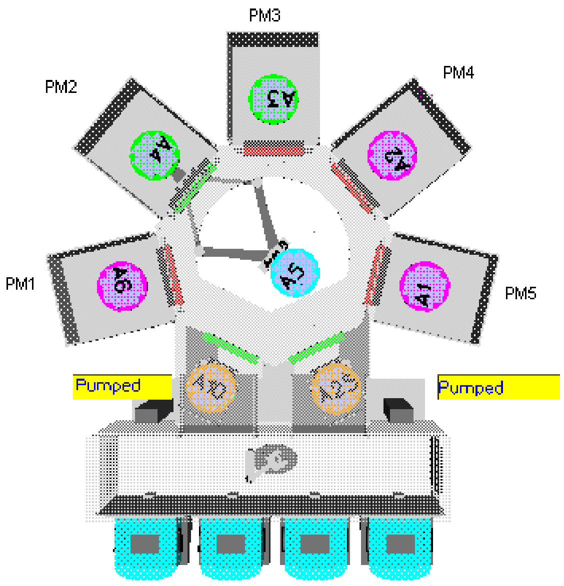

Figure 3: Push Rule Simulation Scheduler

The dual arm vacuum robot selects the most upstream wafer first before beginning the swap sequence. In this example, wafer A6 just swapped with wafer A5 at PM1 and has started processing. Wafer A5 is in the process of swapping with wafer A4 in PM2. Wafer A4 will then swap with wafer A3 in PM3, etc. One end of the robot arm is used as a buffer, while the other end picks or places the selected wafer. Once the robot has rippled downstream and places the last wafer into the loadlock, it searches again for a wafer to begin the ripple sequence, selecting the most upstream wafer first (in this case, a new wafer from the load lock). This example was simplified to illustrate the "push" rule. Obviously, transfer limitations, chamber revisits, and other special rules have been included in this algorithm.

5 EMULATION MODEL

Simulation is an attempt to mimic actual systems. The simulation model was built using a rule-based scheduler, implementing the "push" and "pull" task selection rules described previously. Attempting to mimic the actual CTS in a discrete event simulation model would prove extremely challenging, very time consuming, and possibly have minimal effects with respect to throughput prediction. For this reason, the functionality of the simulation model was extended so that the model can run as an emulator.

Emulation is the process of exactly imitating a real-world system. The simulation model was enhanced to also run as an emulator, using the move sequence provided by the CTS. The results from the emulator are exact with respect to real-world scheduling. When running as an emulator, the simulation model provides the wafer movement and associated tool delays while using the move sequence provided by the real-world CTS.

6 VALIDATING THE SIMULATION SCHEDULER

Scenarios were set up and emulation runs were made using the CTS scheduler and were compared with the exact same scenarios using the simulation scheduler. The results were used to validate the simulation model scheduler, to quantify the throughput differences, and to determine if an adequate search depth for the CTS was used.

The ability exists to simulate or emulate any configuration and product flow using either the simulation scheduler or the CTS. Obviously, the scope of the validation effort needed to be limited. Four categories of configurations and recipe types were chosen to validate the simulation model. The four categories include process-limited flows, robot-limited flows, flows with multiple capacity PMs, and flows that revisit the same PM.

6.1 Process-Limited Flows

A process-limited flow will limit system throughput by one of the PM's processing times. This means that at some point, there will be robot idle time, waiting for the wafer to complete its processing at the limiting PM.

These types of flows include only single capacity PMs. Also, a wafer will never revisit the same PM in this definition of a process-limited flow.

6.2 Robot-Limited Simple Flows

The vacuum robot is the bottleneck on a robot-limited flow. This means that the vacuum robot will never be waiting for a wafer to move.

These types of flows include only single capacity PMs. Also, a wafer will never revisit the same PM in this definition of a robot-limited flow.

6.3 Flows with Multiple Capacity PMs

These kinds of wafer flows include a step where processing occurs at a multiple capacity PM. The multiple capacity PM has an elevator attached to a certain number of shelves. Each shelf can hold and process one wafer, (typically a cool or buffer application). The PM can be processing many wafers independently at any given time. In this study, the PM capacity was set to five.

6.4 Flows that Revisit PMs

These kinds of flows (routes) include separate steps that visit the same PM group. A sample flow, which revisits a PM, is listed below:

Route	Step	PMs	Process Time
route1	1	Orient	5
	2	Ti_1	100
		Ti_2	100
	3	Al	25
	4	Etch	35
	5	Al	25
	6	Cool	40

In this example, each wafer must complete the six-step flow. The wafer is processed in the "Al" PM at step three and at step five. Deadlock avoidance is part of the simulation scheduling rule.

7 RESULTS

Ten test cases were set up for each category to get a snapshot regarding simulation model accuracy. The throughput results, given in wafers per hour, were tabulated. The CTS used a search depth of six for all cases. The results from 10 process-limited flows are tabulated in Table 1.

Table 1: Process-Limited Flow Results

Case Name	CTC Scheduler Throughput	Simulation Scheduler Throughput	% Percentage Difference
Pcase1	35.3	35.3	0.0
Pcase2	45.2	45.2	0.0
Pcase3	45.4	45.2	0.4
Pcase4	38.6	38.6	0.0
Pcase5	35.5	35.5	0.0
Pcase6	26.6	26.6	0.0
Pcase7	54.9	54.9	0.0
Pcase8	59.3	59.2	0.2
Pcase9	37.7	37.6	0.3
Pcase10	74.1	74.1	0.0
Max Difference	0.4		
Min Difference	0.0		
Ave Difference	0.1		

The results from 10 robot-limited simple flows are tabulated in Table 2.

Table 2: Robot-Limited Flow Results

Case Name	CTC Scheduler Throughput	Simulation Scheduler Throughput	% Percentage Difference
Scase1	55.3	55.2	0.2
Scase2	74.0	75.8	-2.4
Scase3	43.5	44.7	-2.8
Scase4	42.5	43.3	-1.9
Scase5	56.5	56.0	0.9
Scase6	42.3	42.1	0.5
Scase7	110.5	110.3	0.2
Scase8	59.3	59.2	0.2
Scase9	115.0	114.7	0.3
Scase10	74.1	74.1	0.0
Max Difference	2.8		
Min Difference	0.0		
Ave Difference	0.9		

The results from 10 multiple capacity PM flows are tabulated in Table 3.

Table 3: Multiple Capacity PM Flow Results

Case Name	CTC Scheduler Throughput	Simulation Scheduler Throughput	% Percentage Difference
Mcase1	63.4	68.4	-7.9
Mcase2	60.5	78.0	-28.9
Mcase3	65.9	82.7	-25.5
Mcase4	73.4	80.6	-9.8
Mcase5	73.8	84.9	-15.0
Mcase6	89.2	90.0	-0.9
Mcase7	51.7	59.7	-15.5
Mcase8	52.9	54.7	-3.4
Mcase9	53.7	58.2	-8.4
Mcase10	51.9	64.7	-24.7
Max Difference	28.9		
Min Difference	0.9		
Ave Difference	14.0		

The results from 10 cases which have loop-back substrate flows (chamber revisits) are tabulated in Table 4.

Table 4: Flows that Revisit PMS Results

Case Name	CTC Scheduler Throughput	Simulation Scheduler Throughput	% Percentage Difference
Revisit1	53.8	42.1	21.7
Revisit2	43.0	42.2	1.9
Revisit3	50.6	47.3	6.5
Revisit4	70.5	63.7	9.6
Revisit5	68.0	53.3	21.6
Revisit6	50.2	51.3	-2.2
Revisit7	54.4	54.4	0.0
Revisit8	70.8	65.2	7.9
Revisit9	49.7	48.8	1.8
Revisit10	71.2	65.2	8.4
Max Difference	21.6		
Min Difference	0.0		
Ave Difference	8.2		

Based on the emulation and simulation results, the following observations can be made:

- The simulation scheduler is very accurate with respect to the CTS for process-limited wafer flows. In all cases tested, the simulation scheduler provided throughput results nearly identical to the CTS.
- The simulation scheduler is very accurate with re spect to the CTS for robot-limited wafer flows. In all cases tested, the simulation scheduler provided throughput results within three percent of the CTS.
- For several robot-limited case flows, the simulation scheduler provided higher throughput numbers. This suggests that a higher search depth may be needed for the CTS when running these cases.
- For multiple capacity PM flows, the simulation scheduler provided significantly higher throughput. This suggests that a higher search depth is needed by the CTS for these case types, or some improvements could be made to the actual CTS scheduler.
- For flows that revisit PMs, the CTS consistently provides significantly higher throughput. This suggests that the simulation scheduler needs to be revised to more accurately mimic the CTS for this type of flow.

8 CONCLUSIONS

Simulation is a cost-effective tool for analyzing and experimenting with new cluster tool designs and alternate configurations. The accuracy of the model is largely dependent upon the simulation scheduler. A validated simulation scheduler can provide confidence in simulation results and resulting design decisions. The ability to observe and compare a real-world CTS with the simulation scheduler has proven valuable in developing the rule-based simulation scheduler and exposing its shortcomings.

The flexible simulation model is a quick and easy tool for running and evaluating different case scenarios. The results of the simulation model for process-limited and robot-limited flows are very accurate. If exact results are needed, the ability exists to use the actual CTS scheduler in an emulation environment.

The benefits of the stand-alone simulation model include ease-of-use, portability, and speed with a high degree of real-world accuracy for specific flow types. The benefits of running the model under the emulation mode include very accurate results.

The limitations of the stand-alone simulation model include some limitations on model accuracy for specific flow types. The limitations of the emulation model include the need to install and run both the CTS software and the simulation model, and the time requirements to set up and run each scenario. Future development efforts include packaging the real-world CTS scheduler into the simulation model, which will eliminate all current simulation limitations.

As a result of this study, improvements to both the CTS scheduler and the simulation scheduler are currently being developed.

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