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MODELING AND SIMULATION OF MATERIAL HANDLING FOR SEMICONDUCTOR WAFER FABRICATION

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ABSTRACT

This paper presents the results of a design study to analyze interbay material-handling systems for semiconductor wafer manufacturing. We developed discrete-event simulation models to model the performance of conventional cleanroom material handling including manual and automated systems. The components of a conventional cleanroom material-handling system include an overhead monorail system for interbay (bay-to-bay) transport, work-in-process stockers for lot storage, and manual systems for intrabay movement. This study examines the models and simulation experiments that assist with analyzing cleanroom material-handling issues such as designing conventional automated material-handling systems and specifying requirements for transport vehicles.

1 INTRODUCTION

This paper presents the performance models and experiments developed to model and simulate conventional material handling for semiconductor wafer fabrication. This paper also includes background information on the characteristics of semiconductor wafer manufacturing and cleanroom material handling. The purpose of these models was to provide modeling tools for SEMATECH members, to generate rules of thumb for automated material-handling system design, and to specify requirements for transport vehicles.

Automated material-handling system (AMHS) design issues include defining capacity requirements for work-in-process (WIP) stockers, comparing various track layouts, determining the effective use of recommended track options, and examining the benefits and the integration of manual and automated material handling. By analyzing specific and generic discrete-event simulation models of wafer fabs with automated material-handling systems, we developed an algorithm that estimates the WIP stocker capacities required for each functional area (or processing bay) based upon inputs such as WIP level and average lot size. The interbay AMHS track configurations explored include spine-based, perimeter-based, and customized layouts. The track options included within this analysis are turntables, turnouts, and high-speed "express lanes" within an overhead monorail system. This paper also presents experiments that compare and contrast manual and automated interbay material-handling with labor hours required, AMHS performance, and wafer fab performance with metrics such as lot delivery time, lot cycle time, and resource utilization's. The transport car simulation experiments in this study establish the sensitivity of vehicle quantities and car velocity to AMHS and wafer fab performance.

2 BACKGROUND

This paper is a result of SEMATECH's partnership with U.S. material-handling equipment suppliers and SEMATECH member companies. SEMATECH stands for SEmiconductor MAnufacturing TECHnology. It is a consortium of U.S. semiconductor manufacturers working with industry, government and academia on vital technical research in the manufacturing of semiconductors. SEMATECH membership includes Motorola, Advanced Micro Devices, AT&T, Digital Equipment, Hewlett-Packard, IBM, Intel, National Semiconductor, NCR, Rockwell, Texas Instruments, and the U.S. Department of Defense. These companies represent 75% of U.S. semiconductor production. The SEMI / SEMATECH organization represents U.S. industry suppliers and serves as their main communications link with SEMATECH and its member companies. SEMATECH is an industry-government partnership developing advanced semiconductor manufacturing processes, materials, systems, and equipment.

One particular area SEMATECH is addressing is factory automation. The goal of this program is to determine the best mix of automated material handling and to assess the merits of revolutionary and evolutionary ideas for material handling. SEMATECH models and then measures these ideas using standard metrics including product cycle time and other system performance measures. This paper represents a type of analysis that evaluates the merits of modeling and simulation of automated material handling.

2.1 Semiconductor Manufacturing

The production of semiconductors is a challenging technological process. The success of operations management and production control techniques are critically dependent upon the availability and performance of highly sophisticated, very expensive process equipment. However, the effective handling of material is also crucial in performing as a world-class manufacturer.

Manufacturing semiconductors, also called integrated circuits or "chips", requires using repetitive sequences of similar processing operations such as photolithography, etch, deposition, diffusion, ion implant, and metallization. Manufacturers produce chips on circular wafers of silicon with diameters ranging from 4 to 8 inches. Groups of wafers, called lots, follow strict process flows and, except for yield losses and engineering splits, usually remain intact while in the fabrication center, also called wafer fab.

A wafer fab typically contains as many as 90 different equipment groups, also called workstations, that require close monitoring to assure stable process performance and high equipment availability. In the more complicated high-volume wafer fabs, approximately 25 active product lines may exist requiring process flows with a series of 300 or more operation steps each.

Because equipment cost is the major capital component (nearly 70%) of today's billion dollar facilities, it imposes that equipment be shared by all lots requiring a certain workstation. Process flows generate repetitive lot movements through a sequence of equipment groups in which a lot may visit the same workstation as many as 25 times during the process cycle. Lots with different maturity will queue and compete for similar workstations causing a highly re-entrant flow, characteristic of semiconductor manufacturing.

Most semiconductor facilities use a job-shop layout for ease of equipment installation, maintenance, and flexibility to accommodate process flow changes. This layout configuration and the existence of highly re-entrant flow, cause lots to travel long distances within a relatively small cleanroom area (20,000 to 60,000 square feet) during the process cycle.

Semiconductor factories can theoretically produce a wafer within a few days under ideal conditions. However, manufacturers (usually in operation seven days per week, 24 hours a day) may measure actual cycle times in weeks or even months. These long queue times are attributable to system variability such as product mix, process instability, unscheduled down time, or product quality problems. Mismatched equipment run rates, varied product dispatch strategies at each workstation, and long process times of batch operations create an asynchronous system, increasing queue times that greatly contribute to increases of cycle time.

2.2 Cleanroom Material Handling

Most eight-inch diameter wafer fabs are reliant upon mechanized interbay transport systems and manual intrabay handling to move lots from step to step. While the AMH systems are certified to be cleanroom compliant, manufacturing operators are required to "gown" up from head to toe to prevent particle contamination. Proper material-handling practices reduce yield loss caused by contamination, vibration, and electrostatic discharge.

As the diameters of the wafers have increased, naturally the dimensions and weights of wafer carriers have also increased. A typical carbon powder lot box containing a carbon powder cassette with 25 eight-inch wafers weighs 7.4 lb. Total weights of other carriers such as self-contained wafer pods or Teflon cassettes may weigh up to 12 lb. This weight factor has provoked several semiconductor companies to participate in job design changes to increase fab ergonomics that improves productivity and makes the job safer. Many mature wafer fabs attribute their largest yield loss to wafer breakage due to manual mishandling. For these reasons, AMH systems have become an effective way of moving lots within a fab.

3 MODEL DEVELOPMENT

Performance models were created to assist users to design new material-handling systems as well as to examine and enhance systems in operation. Several validation experiments produced acceptable results for each model. However, additional data collection was necessary for some kinematic elements associated with

AMHS equipment. Each of the following models and/or their explicit results is available to SEMATECH members.

Three AMHS performance models were developed on personal computer using SIMAN/CINEMA V from Systems Modeling Corp. and AutoMod/AutoSched from AutoSimulations Inc. Animation aided in designing the systems, verifying input data, and demonstrating the model. In each application, discrete-event simulation proved to be a very useful tool in analyzing the performance of material-handling systems.

3.1 Generic Interbay AMHS Model

The Generic Interbay AMHS Model enables users to model an AMH system in sufficient detail without having to model the process equipment and manual systems in their operation. Users may model WIP stocker activities including automated input/output (I/O) queues and I/O designs such as dedicated or flexible ports. The model also measures utilization's of automated storage/retrieval systems (AS/RS) and stocker storage capacity. The transport system in this model can be designed with a spine or perimeter-based track layout. A user menu establishes turnout location, car parking and vehicle attributes. This model uses a process time multiplier along with a percentage deviation as a queuing factor in place of modeling the availability of processing tools and operators. A spreadsheet inputs process flow sequences with equipment types and processing times. This model was developed in SIMAN/CINEMA V on the DOS operating system. Although validation is on-going, the Generic Interbay AMHS Model has been useful for quickly generating a model of an AMH system in a wafer fab.

3.2 Automation Test Facility Model

The Automation Test Facility Model, see Figure 1, was created in AutoMod/AutoSched to model SEMATECH's Automation Test Facility (ATF). The ATF laboratory is an 18 X 50 foot class 1 (one airborne particle greater than 0.5 micron in size per cubic foot of air) cleanroom bay integrating AMHS equipment from eight U.S. suppliers into a single interbay AMH system. WIP stockers from three different manufacturers (Precision Robots Inc., Proconics International, and Programmation -- now owned by Precision Robots Inc.) are integrated with an overhead track. A vertical transfer and a queue loop are also part of the ATF. There are three other suppliers supporting automated identification systems such as short and long-range infrared as well as short-range radio frequency technology. A material control system (MCS) and an intrabay material-handling track robot are also components of the ATF.

The ATF Model was created in two separate systems, a detailed kinematics version and a version that uses the AS/RS constructs within AutoMod. The kinematics version uses empirical data for all robotic movements. The AS/RS construct version uses inputs for horizontal, vertical, and creep velocities as well as rates for acceleration and deceleration. Execution times for each model were relatively the same.

The validation plan had two phases. The first phase included timing each possible point to point stocker robot and car movement (12) and comparing these values to the times generated by the model. The basis of this examination was to identify which travel segments or stocker delays required additional data or code review. Both versions of the ATF model produced results well within 10% of the actual move times for the first validation phase.

The second validation phase involved a series of scenarios comparing total lot movements from the actual system and the model. The final experiment in this phase involved transporting eight lots on random paths with four cars (single lot loads) for five hours. Again, both versions of the ATF model produced results within 10%.

During this project we learned two interesting things previously unknown about the ATF system and we made an evaluation of AutoMod as a simulation package for modeling material-handling systems. The first observation we uncovered about the ATF came during the data collection phase when we timed the communication delays between the WIP stockers and the MCS. Depending upon the stocker and whether lots were interacting with input /output ports or track Pports the communication delays varied from 3 to 10 seconds. Although brief, these delays accumulate and would invalidate this model if ignored. The transport car velocity was a source of indecisive data. ATF transport cars travel short distances through curves, turntables, and control stations when moving from one location to another. Because of these track variations and our inability to measure acceleration and deceleration rates, it was a challenge to measure and determine our car speed. We did calculate an overall velocity that included the affects of acceleration and deceleration. Kinematic elements were developed for each component of the ATF to provide detailed examinations and evaluate incremental modifications. However, considering that the accuracy of the AS/RS constructs version was just as good as the kinematics version and required less than half the effort to develop, we encourage the use of the AS/RS constructs over the kinematics option when modeling WIP stockers or similar equipment.

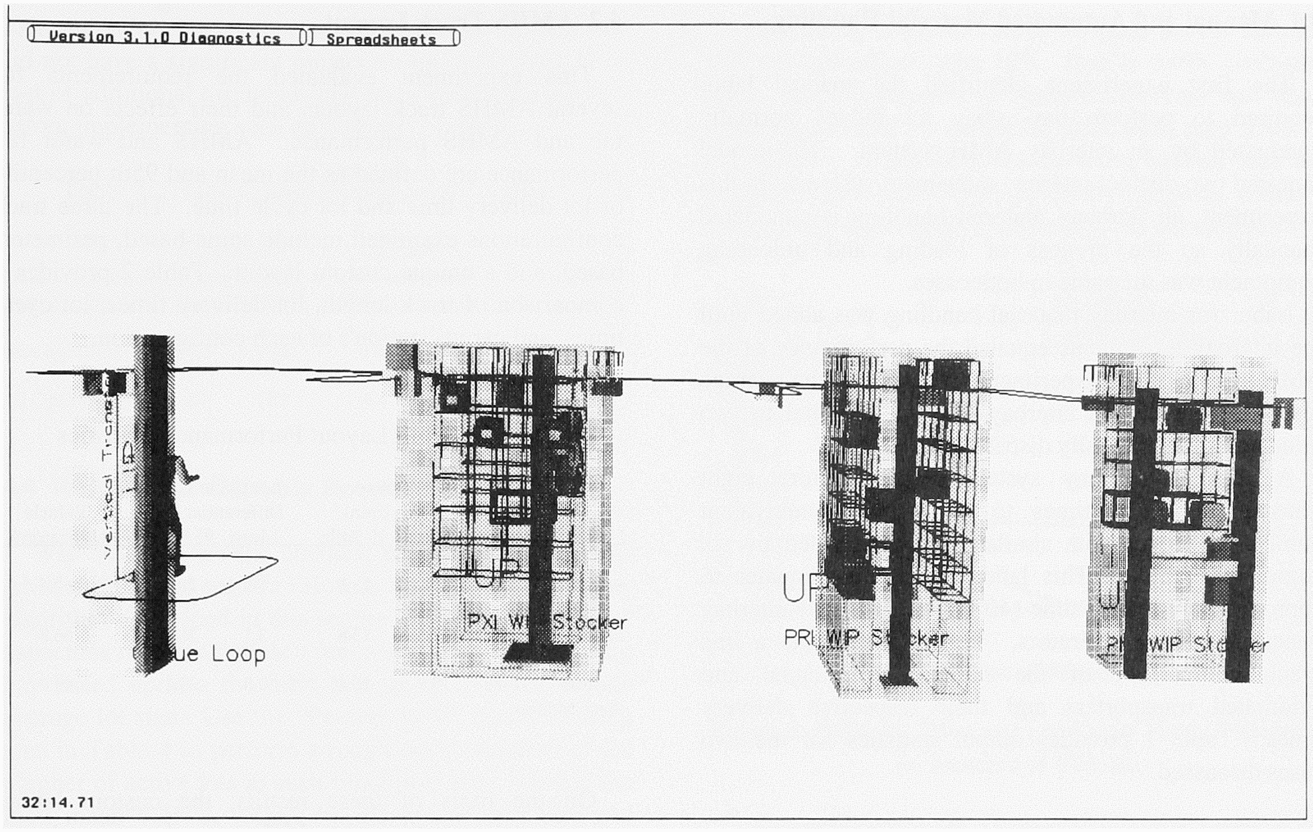

Figure 1: ATF Model Animation Screen including Vertical Transfer, Proconics Stocker, Precision Robots Inc. Stocker, and Programmation Stocker

It is our conclusion that AutoMod was an ideal simulation package for this application. AutoMod has embedded material-handling constructs that emulate overhead monorails and stockers with a high level of accuracy and detail. The three dimensional animation capability was extremely useful in verifying the model.

3.3 Full-Flow AMHS Model

The Full-Flow AMHS Model is a prime case study of an actual interbay AMHS installation of a wafer fab. We developed this model in AutoMod/AutoSched. This eight-inch wafer fab has 36,000 square feet of cleanroom space. Ultimately, it will have capacity for 20,000 wafer starts per month requiring an average of 110 interbay transports per hour.

Although this wafer fab has an overall spine-based layout, the AMHS track scheme was customized greatly to distribute WIP stockers in the center of each bay and to enable transport vehicles to travel through openings in the cleanroom walls. This layout shortens the distances for manual intrabay material handling by concentrating the WIP to the middle of each bay. Battery powered vehicles travel overhead on a unidirectional track system made up of 1,500 linear feet and several turntables. This model was used to produce the simulation experiments presented in this paper and to provide a successful case study for the modeling and simulation of material handling for semiconductor wafer fabs.

4 EXPERIMENTS AND ANALYSIS

The Full-Flow AMHS Model, driven by AutoStat, provided this series of simulation experiments. However, other models from SEMATECH's Factory Automation group and SEMATECH members also provided analysis that supported these conclusions.

The following measures and assumptions were included in our analysis. The model reached steady state after a 180 day warm-up period. Mean results were calculated from four replications of 60 day run lengths from the steady state initial condition. Lot cycle times are presented as differential values from the base case installation. The base case version was determined to require six AMHS cars traveling 100 feet per minute on a custom track configuration serving a fab with 240 lot starts per month.

4.1 Manual and Automated Material Handling

The first experiment identified the manual labor required to perform bay-to-bay lot moves normally conducted by an interbay AMH system. The model required two distinct interbay movement systems. In this experiment, all intrabay material handling is conducted manually so the process of loading and unloading equipment was the same in both cases.

Labor for interbay material handling was added until the interbay movements equaled the performance of the AMH system. This experiment assumes that the average response time for an interbay operator is equal to two minutes exponentionally distributed.

A manual interbay system would require eight transporters at all times to perform the equivalent number of moves with similar results provided by six automated vehicles. This labor requirement equates to approximately 34 full-time (40 hours per week) interbay material-handling operators. Figure 2 presents a line graph comparison of the number of manual and automated transporters and their respective delivery times. Table 1 provides output statistics for the two cases discussed.

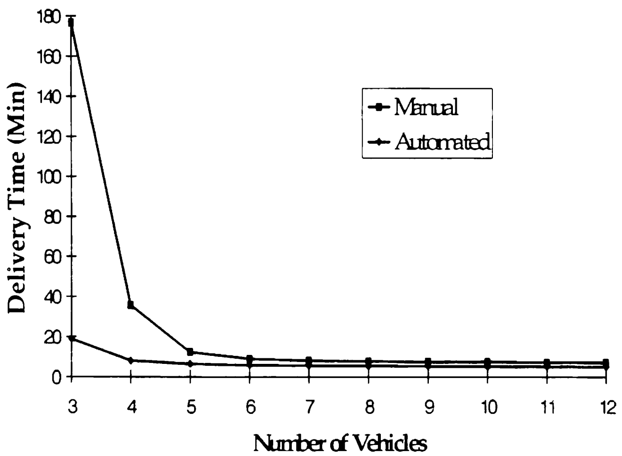

Figure 2: Delivery Time vs. Number of Manual or Automated Transporters

Table 1: Performance Statistics of Manual and Automated Transporters

Track Design	Number of Transporters	Lot Delivery Time (min) Mean	95 %tile	Lot Cycle Time Differential (hr) Mean	95 %tile	Vehicle Utilizaton%
Manual	8	9.7	14.2	8.4	42.7	52.2
Automated	6	5.9	10.4	0.0	33.1	49.9

4.2 AMHS Track Layout

This experiment evaluated the requirements for several AMHS track layouts and their effects on wafer fab and AMHS performance. AMHS and wafer fab performance are defined as the mean and 95th percentile of lot delivery time and lot cycle time. The three track configurations examined include spine-based, perimeter-based, and a unique custom layout. Table 2 provides a comparison of track length, lot delivery times, lot cycle times, and car utilization's of each configuration.

Table 2: Track Layout Performance Statistics

Track Design	Track Footage	Lot Delivery Time (min) Mean	95 %tile	Lot Cycle Time Differential (hr) Mean	95 %tile	Vehicle Utilizaton%
Spine	621	7.0	13.8	1.9	28.0	60.6
Perimeter	820	7.5	15.8	3.1	36.7	66.8
Custom (Base Model)	1473	5.9	10.4	0.0	33.1	49.9

On the basis of these results, the custom layout reduces delivery times by 16% over the spine based configuration. However, the custom layout requires more than twice as much track. The perimeter layout has the worst performance and requires more track than the spine based configuration. Because car utilization's' were under 67% in all cases, the layouts had no significant effect on the mean lot cycle time.

4.3 Track Options

This experiment examined a variety of track options used to improve AMHS and wafer fab performance. AMHS and wafer fab performance are defined as the mean and 95th percentile of lot delivery time and lot cycle time. The track options include turntables, turnouts, and high-speed express lanes. Turntables control an intersection of several tracks by rotating cars to appropriate track segments. Turnouts are similar to railroad track switches that permit moving cars to veer off to another track segment. Turnouts are commonly used by AMHS cars to access parking areas. An express lane can be as basic as a single track segment with minimal interference or it may be a specialized, and sometimes separate, track system used for longer moves at higher speeds.

Table 3 provides output statistics of the base case version and a system composed of 10 additional turntables and several express lanes. The results suggest that the maximum use of track options would provide a

20% reduction in delivery time. However, this system did not have a significant impact on lot cycle time. The cost of additional turntables and track must be examined before implementing such an elaborate system.

Table 3: Track Option Performance Statistics

Track Design	Track Footage	Lot Delivery Time (min) Mean	95 %tile	Lot Cycle Time Differential (hr) Mean	95 %tile	Vehicle Utilizaton%
Base Model	1473	5.9	10.4	0.0	33.1	49.9
All Options	1890	4.7	15.2	-6.4	25.6	42.3

4.4 WIP Stocker Capacity Requirements

WIP stockers are the costliest part of a conventional AMH system and require valuable cleanroom space. The algorithm developed in this section estimates the stocker capacities required for each functional area or processing bay based upon a the fab's average WIP level and its average lot size. Use the "Percent WIP" factor for each area in Table 4 to perform a rough-cut calculation of the number of active lots in each functional area. Divide the fab's mean WIP in wafers by the average lot size and multiply by the respective "Percent WIP" factor to obtain the average number of lots in each area. Areas with multiple bays usually distribute their WIP evenly between each bay.

Table 4: Percent WIP by Functional Area

Functional Area	Percent WIP
Diffusion	45
Films	12
Implant	12
Photolithography	10
Etch	10
Probe	4
Metals	4
Backgrind	3

4.5 Transport Vehicles

This experiment establishes the sensitivity of the quantity and velocity of automated vehicles to AMHS and wafer fab performance. Again, AMHS and wafer fab performance are defined as the mean delivery time and lot cycle time.

Figure 3 presents a comparison of the number of vehicles and their respective delivery time and lot cycle time. AMHS performance is enhanced with additional vehicles until ten cars are included within the system. However, reductions in delivery times are minimal after the sixth car is in place. Lot cycle times are not affected until car utilization's pass 70%. Due to traffic controller logic, the combination of many (15+) cars and short distances, created by numerous turntables, may result in a gridlock. A gridlock occurs when several cars are queuing for vehicle zones or control stations within a closed loop without openings for any car movement.

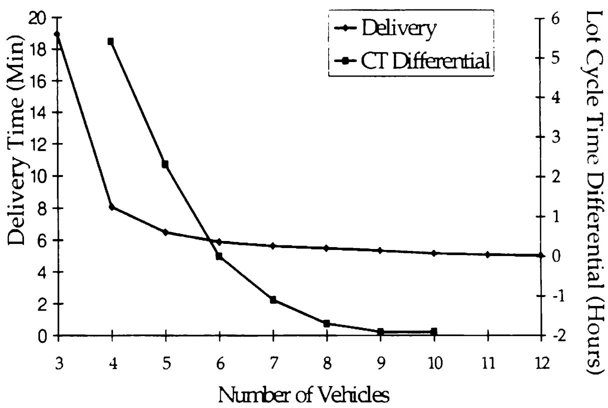

Figure 3: Delivery Time and Lot Cycle Time Differential vs. Number of Vehicles

The final experiment compared the performance of car velocities of 60, 100, and 140 feet per minute. Figure 4 provides a line graph with various vehicle speeds and quantities with their respective delivery times. Faster cars reduce the number of cars required to service a wafer fab. For example, the base case model required six cars traveling 100 feet per minute while a system using cars with speeds of 60 feet per minute would require approximately eight cars to achieve similar delivery times. Naturally, faster cars tend to be more beneficial on track layouts with longer distances and less congestion than with configurations with shorter segments and more traffic.

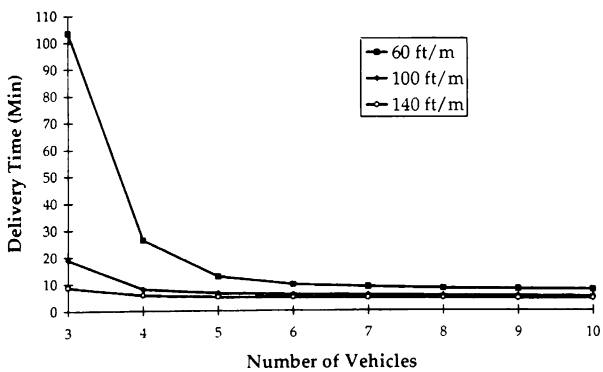

Figure 4: Delivery Time vs. Number of Vehicles with Different Velocities

5 SUMMARY

This paper presents the models, experiments, and design rules developed to analyze interbay material-handling systems for semiconductor wafer manufacturing. Discrete-event simulation models were developed to model the performance of conventional cleanroom material handling including manual and automated systems. We examine the models and simulation experiments that assist with analyzing cleanroom material-handling issues such as designing conventional automated material-handling systems and specifying requirements for transport vehicles.

Discrete-event simulation proved to be an ideal tool for evaluating material-handling system performance. The Full-Flow AMHS Model included manufacturing operations and material handling required for all interbay movements. The model provided key insights on material handling for semiconductor wafer fabrication.

One experiment compared manual and automated interbay material-handling systems. This experiment showed that 34 operators, dedicated to interbay transport, would be required to move lots between bays with the same performance as six AMHS cars in our base case example. Other experiments examined AMHS performance issues such as track design, track options, number of transport cars, and vehicle speed. Track design has a significant impact on delivery times. Average delivery times for AMHS track configurations ranged from 5.9 to 7.5 minutes compared to the average delivery time of 9.7 minutes from the manual system. The best track layout was a custom design that creates the shortest path obtainable. The performance of the base case AMHS design can be improved by nearly 20% by adding 10 more turntables and 500 feet of track. However, the cost and benefit of these additions should be examined further. Vehicle count and velocity can effect system performance especially if a less effective track layout is used. Faster cars may slightly reduce the number of cars needed and/or increase AMHS capacity in terms of transports per hour. Vehicle count and velocity should be selected carefully since the lack of capacity will cause system performance to degrade exponentially.

The most practical approach to enhancing interbay AMHS performance is to minimize the travel distances between stockers by using a custom track layout with turntables. This study examined the effects of interbay material-handling systems on lot delivery times and lot cycle time. Although there were many characteristics that proved to be sensitive to lot delivery times, these characteristics had no impact on lot cycle time for wafer fabs with adequate material-handling capacity.

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