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SIMULATION IN AUTOMATED MATERIAL HANDLING SYSTEMS DESIGN FOR SEMICONDUCTOR MANUFACTURING

Gajanana Nadoli
Devadas Pillai

Design Engineering
Automated Material Handling Systems
Intel Corporation
5000 W. Chandler Blvd.
Chandler, AZ 85226.

ABSTRACT

We present the simulation methodologies used in the design of Automated Material Handling Systems (AMHS) at Intel wafer fabs. The models used in AMHS design can be categorized as AMHS models and production models. The AMHS models support the design of Interbay and Intrabay systems. The Interbay systems handle the material flow between different bays (production centers). The Intrabay systems handle the material flow within the bays. The production models compliment the AMHS models. We review the general model structures and simulation examples under these categories used in actual system implementations.

1 INTRODUCTION

In semiconductor manufacturing, the silicon wafer product is very delicate and prone to develop defects due to particle contamination or excessive vibrations. Automated Material Handling Systems (AMHS) provide the benefit of controlled and predictable material delivery (Raymond, 1988) in a clean environment. An added benefit is the reduction in particle contamination and vibrational shocks on the wafers compared to manual handling (Intel Corp., 1991).

The AMHS for semiconductor manufacturing can be categorized as Interbay and Intrabay systems. An Interbay system moves and stores the wafers during their transit between the production centers or bays in the facility. Each bay has an automated storage and retrieval system or Stocker that acts as the interface point for the material movement in and out of the bay. A monorail system interconnects these Stockers. An Intrabay system moves and stores the wafers during their transit between the Stockers and the production equipment.

The main objective of using simulation here is to ensure that the material handling system design meets material storage and transport requirements. One can model the rules and constraints in the system in detail and predict the performance bottlenecks in the system prior to installation. We review the general model structures and simulation examples used in actual implementations.

2 ROLE OF SIMULATION IN AMHS DESIGN

The design of an AMHS for a new manufacturing facility is an iterative process that can be summarized as follows:

i) Requirement Evaluation: Determine the storage and material flow requirements based on the process flow from one bay to the other.
ii) Preliminary Design: Determine the layout of the material handling equipment such as Monorail routing and Stockers.
iii) Analysis of Alternative Designs: Evaluate the performance of various configurations and their variations.
iv) Design Detailing: Develop detailed specifications of different components keeping in view the mechanical, controls, and safety considerations.

The analysis methodologies and tools have played a critical role in the design process at Intel (Pillai, 1989, 1990). The first two steps require the use of heuristics-based techniques. Simulation is typically used in the third stage. Also, during the implementation stage, simulation models help to generate test conditions to test the systems prior to commissioning.

2.1 AMHS Modeling Philosophy

The stochastic nature of the production activity produces variable loading conditions on an AMHS. In a modeling context, we can envision two approaches to analyze the behavior of such systems. The first approach considers the production processes and the material handling systems as parts of an integrated system, modeling each of them in detail in a single model. The second approach considers the production processes and the AMHS as two coupled systems with explicit input-output relationships, modeled separately.

We use the second approach. This approach is valid under two pre-conditions. First, the details of the input flow and output flow at each process step is known in enough detail. Second, the AMHS and the production process models use a consistent set of assumptions. This de-coupling approach typifies our general philosophy to using simulation in design. Different models answer different questions. Building a single model (of a new factory) in a reasonable amount of time to answer all the answers for a large system such as a semiconductor facility is not feasible.

Table 1 lists the models we discuss in this paper. The AMHS models provide the performance metrics of the material handling systems in the form of delivery times, storage requirements, and transport congestion points. The production models provide the indicators of bottleneck machines and work-in-process "bubbles."

We have used a mix of tools for model development. These include: Automod/ Autosched (AutoSimulations, 1993), Mansim (Tycin, 1992), SIMAN (Systems Modeling Corp. 1989), and Modsim (CACI, 1993).

A detailed analysis stage precedes any simulation, since we need to understand the material flow requirements between bays and between equipment for Interbay and Intrabay systems respectively. These requirements in the form of "from-to-charts" form the inputs that drive simulation models. The rate of creation and the variation in the rate of creation depend on the historical profiles observed in the similar steps in existing factories. The simulation models explicitly consider the instantaneous surges in the load placed on the system.

Table 1
Models Used in AMHS Design

Model Category	**Model Objectives**
AMHS Models	**Interbay AMHS Models** Determining Interbay system performance indicators Designing Reticle transport systems **Intrabay AMHS Models** Determining the Intrabay system performance indicators Determining the impact of process equipment failures Models for intelligent AGV Scheduling
Production Models	Evaluating work-in-process profiles

3 AMHS SIMULATION MODELS

3.1 General Structure

It is critical to model the spatial features of an AMHS since they have an impact on the system performance. Typically these models have a segment that models the layout and a segment that models the logic for lot arrivals, control systems, vehicle logic, etc.

A system may use either ground-based automated guided vehicles or overhead Monorail vehicles. In both cases, the nature of interactions of the vehicles, storage devices, and AMHS controller is the same. Typically the computer controls are elaborate and complex. The control system capability varies greatly from one AMHS supplier to another. The control system capability of the system determines the flexibility available in configuring the Monorail tracks. At Intel, we have built extensive simulation models embedding the vehicle control characteristics.

The locations on the track where the vehicles receive command instructions from the material handling controller, stop for traffic reasons, or stop for pickup or drop-off of material have sensors or control elements. The placement of these sensors or control elements is based on layout constraints such as vehicle sizes, collision avoidance zones, and track segment types (curved or straight). The velocity, acceleration, and deceleration of vehicles at different points in the track form the input parameters of a model. The vehicle travels at different velocities at straight sections, curves, spurs, and intersections. Sometimes, a vehicle may travel at different velocities depending on whether it carries a load or not. Another critical assumption is the vehicle stop to start time, which is defined as the time required for the vehicle to stop, either pick up or set-down a load and start moving. This factor has an impact if a vehicle blocks other vehicles when loading or unloading. Several simulations at Intel have shown that this is a critical design parameter for meeting throughput.

The key ingredients of the model are material movement control and vehicle control. The "from-to-charts" derived from the process flow determine the material movement control. The vehicle control logic varies from one supplier to another. Some of the typical vehicle control features are:

1. Work search locations and priority for vehicle allocation based on closest distance at which a free and unallocated vehicle is available.
2. Parking locations, either at the point where the vehicle last dropped off a load or at designated locations.
3. Bumping logic - a procedure which a "sleeping (unallocated) vehicle" is awakened and asked to move and park elsewhere, due to another vehicle coming with a load bound for or passing that location.
4. Opportunity battery charging logic, or battery change logic, which mimics vehicle unavailability while the vehicle is either getting a battery charge or undergoing a battery change.
5. Dedication of specific vehicles to specific loops, to ensure that all connected loops of the AGV system gets the required number of vehicles to meet transport needs.

Simulation sensitivity analyses are performed by changing the vehicle control features that have the option of being changed based on user needs. This includes changing work search locations and the order in which these lists are scanned, parking lot locations and the number of vehicle allowed to park at parking lots, and dedication of vehicles to specific loops. In addition, a common variable that gets changed is the number of vehicles servicing the system. The changes to track locations and their placement are also common. Typical design objectives are to minimize waiting time for a lot to get a vehicle, to minimize number of lots waiting for vehicle, to minimize point to point transport time, and to minimize vehicle utilization and congestion.

3.2 Interbay AMHS Models

The Interbay models have a structure shown in Figure 1. Each bay has at least one Stocker. The lots originate from Stockers using the Interbay system to move to their destinations. The lots arrive at the destination Stocker and they move out of the system being modeled. We have used simulation in the design of about eight different base systems or modifications so far.

When moving from one Stocker to another, a lot may move into an intermediate storage point depending on the operational conditions specified in the model. The input parameters of interest are: operation assignment to production bays, production rate, and batch sizes. For each of the flows to be handled by the Interbay system, the simulation model creates and sends the lots from source to destination Stockers.

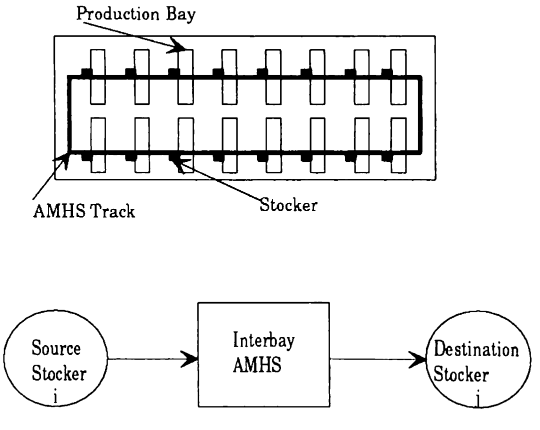

Figure 1. A Typical Interbay Model Architecture

Model Logic: The layout and other configuration parameters such as number of vehicles, speed, acceleration, deceleration, and a default logic of routing the vehicles to the pick up and drop off locations are user inputs to the model. The simulation modeler can override the default behavior of the components of the system. The typical variations in the flow logic that requires explicit coding are:

i) Lots going from *i* to *j* may not have a straightforward path. For example, if a single track does not connect *i* and *j*, the lots may have be transferred between two tracks via systems such as conveyors, bridges, etc.

ii) The location *j* may not have enough storage to move the lot. In that case the lot needs to move into an intermediate location *o* (called overflow storage) and then move to location j as and when the space becomes available.

iii) The available number of locations in a destination conveyor may be zero. Moving the lots to that location may lead to deadlock situations.

iv) The track may have a by-pass that should be used by a vehicle when the main path is blocked by another vehicle loading or unloading at a Stocker.

v) The vehicle may have delays when starting to move or starting to load or unload, that may be because of specific control system delays.

We discuss two examples of Interbay models.

Determining Interbay AMHS System Performance Indicators: The objective of this analysis was to gauge system performance indicators based on an increased loading trend. We identified potential system congestion and bottleneck areas and modified system usage around these areas to ensure smooth material flows. The key areas that were evaluated as a measure of system performance were the following:

Utilization of the Stocker robots The simulation results showed that in those bays were batch sizes were greater than one, the ratio of peak utilization to the average utilization of the Stocker robots were higher. It was also clear that the average utilization of the Stocker robots was directly proportional to the number of process steps in each bay. The design team decided on a cut-off point for the peak utilization of the Stocker robot, and whenever the peak utilization exceeded this point, a decision was made to use more than one Stocker robot for that bay. Final determination of multiple Stockers in each bay was finalized only after it was determined that space was available for the additional Stocker.

Wait times at a Stocker for an Interbay vehicle This is another excellent indicator in terms of whether any point in the Interbay path was not being serviced by empty free vehicles. This told the design team that changes had to be made to the vehicle scheduling algorithm in order to ensure service to all potential points in the layout where loads would appear. The changes would increase or decrease the priority of the loads to be picked up at different locations.

Transportation time on an Interbay vehicle This performance indicator tells the design team the expected "delivery time" for transport from one bay to another. This is critical because this time gets potentially gets added to the total cycle time for the manufacturing process or the operators end up waiting for requested material resulting in lost productivity. The objective of the simulation is always to minimize the transportation time from bay to bay.

Vehicle capacity lost due to traffic congestion Adding Interbay vehicles to the track in excess of what is really required results in increased vehicle congestion, sometimes leading to long and extensive transportation times and gridlock. An indicator called "vehicles lost due to congestion" was used which tells the designers the percentage of time a vehicle (either loaded or empty) was blocked by a vehicle just in front of it. Since this is wasted time, decisions were made to reduce vehicle quantities one at a time and observe its impact on both wait times at a Stocker as well as transportation times. Figure 2 is an example of a sensitivity analysis. In this particular case, the recommended number of vehicles to be used was 23. This minimized vehicle configuration while guaranteeing meeting throughput requirements.

Designing Reticle Transport System: The design of Reticle transport systems for Lithography Reticle mask storage and delivery is very similar to the Interbay transport system. The request for Reticle delivery is a function of the lots processed between sequential Reticle changes in the Fab. In some Fabs, a Reticle may be requested once for every four to six lots processed on the Lithography equipment. In other fabs, such as in ASIC production, the lots between Reticle changes may be as frequent as one lot. In the second case, the Reticle transport system is very busy when compared to the first case.

The same parameters used to evaluate the performance of AMHS systems for Interbay are used in the case of Reticle transport systems.

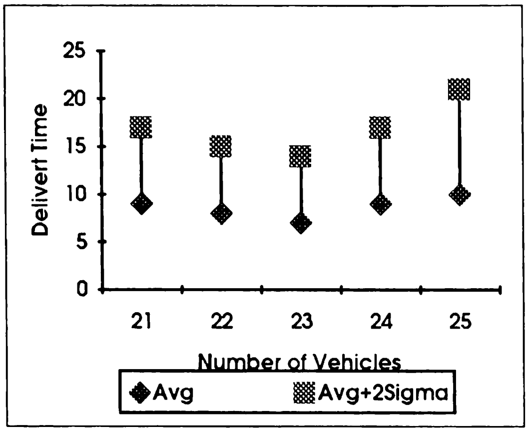

Figure 2. Impact of Adding Vehicles to Total Delivery Time

3.3 Intrabay AMHS Models

The Intrabay simulation models have a structure as shown in Figure 3. The Intrabay systems move lots from the bay Stockers to the machines within the bay. The types of vehicles may be of ground-based or overhead type. Additional complexity of Intrabay systems arises due to the need to manage multiple carriers (Walsh and Tyra, 1992). Typically the wafers held in cassettes are transported within another box in the Interbay system. As these boxes enter a bay, cassettes have to be removed, empty boxes have to be stored, and the cassettes have to be handled by the Intrabay vehicle. The Intrabay systems also need to handle the process-dependent materials (such as test wafer lots). Simulation has been used in the design of three such major systems so far.

The input parameters of interest are: operation assignments to the set of production equipment within the bay, batch sizes, processing times, batching criteria, etc. For each of the steps assigned to a bay, the simulation model creates and sends the lots to the bay Stocker. The rate of creation and its variation is dependent on the operation of the equipment upstream.

Model Logic: Similar to the Interbay models, model development proceeds from the base model specified from the graphical user interface to the process-oriented logic definition. The typical variations in the flow logic that require explicit coding are:

i) Lots may need to wait for synchronization conditions.
   Examples: batching, buffer loading, tool replacement, reservations, etc.
ii) Auxiliary flow of materials. Eg., replenishment of dummy wafer and test wafer lots.
iii) Special scheduling mechanisms for material handling system entities. Eg., Stockers and Intrabay vehicle(s).

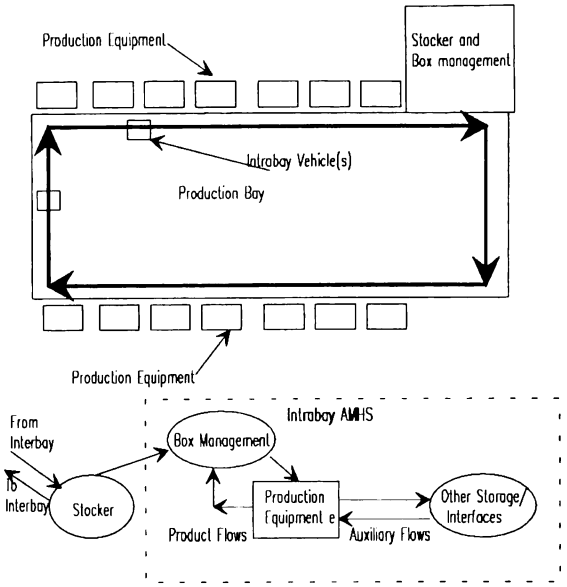

Figure 3. Common Structure of Intrabay Models

We discuss simulation studies that were done as part of a project. That Intrabay system consists of multiple lines of rail guided vehicles (RGVs). Each RGV serves multiple Diffusion furnaces on one side of the bay. Each line consists of Stockers for boxes-with-cassettes, empty boxes, and cassettes. A box-cassette management system handles removing the cassettes from boxes and placing them back when needed. The project required several iterations of simulation analysis during its design cycle (Nadoli, 1993).

Determining Intrabay System Performance Indicators: Similar to Interbay systems, the Intrabay system performance indicators include Stocker utilizations, waiting time for a vehicle, delivery time, and vehicle utilization. The Intrabay delivery time is crucial since it directly impacts machine utilization. Tardy delivery performance results in equipment starvation and reduced output. Some furnaces may have buffers to stage the material and hide delivery time considerations.

The objective of the initial analysis was to determine the number of machines that can be served by a vehicle under maximum loading conditions. This would then set the design limits for the system. Figure 4 shows the delivery time as a function of the number machines served. The vehicle utilization also showed a similar trend. We adopted Case 4 as the design number for a typical line.

A second simulation model was developed after actual loading conditions were known for typical line of furnaces. We considered three production levels (base, base+10%, and base+15%). Simulation results showed that in the second and third loading conditions, production capacity was not sufficient to meet throughput. Also, the material handling system was not the limiter on the system throughput (As a rule, the support systems such as AMHS should never be production limiters). System statistics such as delivery time, number of lots waiting for the vehicle, number of lots moved per hour, Stocker cycles per hour, box management system cycles per hour, number of boxes-with-cassettes, number of empty boxes, and number of cassettes in the system were collected. All of these met design and operating constraints.

After completion of the design we found that the batch size handled by the furnaces in the bay increased by fifty percent. However, the design limit we had established in the original set of studies was under conservative (expected worst case) loading conditions. Though the batch delivery time increased (since the RGV had to make more trips for a batch), it was in an acceptable range.

Determining the Impact of Machine Failures on RGV Line: Any of the furnaces that need front access during repair can block the RGV line during that repair time. Given the number of machines on each side, we needed to understand impact of machine failures on availability of the RGV system for material delivery. We used a simple analytical model to estimate the probability of x occurrences of RGV blockages given that there are n furnaces in a line. This model considered the distribution of the number of failures per week for each machine is Poisson and aggregated the number of failures over n furnaces during a week. Analysis showed that the probability of blockage doubles when the number of machines increases from a base case. This led the design team to recommend placing the Stocker in the middle. So even if one of the sides is down, the other side can be serviced by the RGV. The simulation model was modified slightly to estimate the recovery profile of the system after a failure with this configuration.

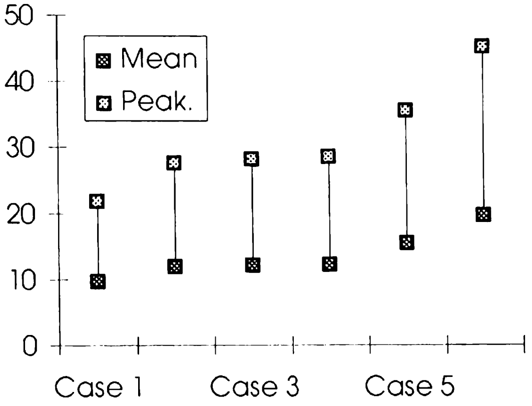

Figure 4. Intrabay Delivery Time as a Function of the Number of Machines

RGV Capacity and Scheduling: The Intrabay RGV is a single vehicle resource serving multiple delivery requests from furnaces. Scheduling schemes used for the vehicle have an impact on the performance. Since the RGV has the capability to carry multiple lots, it can pick up lots opportunistically on the way if it has remaining capacity. We tested different algorithms and different capacities of the RGV before determining the final configuration. We discuss one of these algorithms to illustrate the importance of incorporating the control system behavior in simulation.

Suppose the RGV has dropped off lots at a furnace. The requests pending at that time may have different priorities. After selecting the highest priority lots from a machine (say, primary work location A), the empty vehicle moves in that direction. The vehicle reserves the space for the number of lots at location A. The vehicle can now opportunistically pick up and drop off lots along the way. This is analogous to an elevator's operation.

Suprisingly, in our case, simple FIFO scheduling and the opportunistic scheduling did not show any significant difference in performance. This, we suspect, was because of the batch nature of the processes and the additional delays incurred when picking up the lots opportunistically.

4 PRODUCTION MODELS

Production models are used in tandem with AMHS models as described earlier. For the purpose of AMHS design, the production models provide two main inputs: i) the lot arrival profiles from process steps and ii) the Stocker storage requirements.

The models we have used in this area include specific models developed in general purpose languages and simulators (Examples: Mansim, Autosched). Simulators provide modeling templates that can be modified with varying levels of flexibility.

Models for Evaluating WIP Profiles: In factories where automated storage and handling is the norm, the design of manufacturing systems and methods should fully comprehend the WIP (work in process) storage requirements and its variability over time in each production bay. This is particularly significant if the feeding process equipment has a batch size different from the receiving process equipment, or if the process equipment is subject to frequent machine failures that lead to un-anticipated inventory surges into that functional area of the factory. The main focus in these kinds of simulation models is to obtain guidelines in determining the following operational parameters: (1) the number and types of each kind of process equipment required for each bay, (2) total quantity of storage locations and buffer locations required for each production bay, (3) preferred equipment layout option, (4) material routing and entering/exit rules for each bay, and (5) operational policy during normal modes as well as during modes when certain equipment faced large downtimes, causing it to becoming a temporary bottleneck to production. During these anomaly periods, the models have shown that the load arrival frequency distribution is very different from the normal mode of operations, and it has caused the team to look at that aspect in very fine detail. Simulation is used extensively to understand this load arrival variability as well as the typical load residency patterns during anomalies. These studies have also concentrated on understanding the optimum level of buffering that is required for ensuring that consistent output is still being met during periods of catastrophic process equipment failure modes. These studies have given rise to further exploration on inventory load balancing across bays, all aimed at reducing work in process inventory as well as controlling its variability.

Simulation models in this area have clearly illustrated that great attention need to be placed on modeling system randomness, understanding and applying the correct probability distributions, and modeling machine failure patterns. Particular attention should be paid to probability distributions of arriving loads into each functional area by load type, as well as distributions for Mean time between Failures (MTBF) and Mean Time to Repair (MTTR). Isolating actual repair time from the technician response time (each of which could have its own unique probability distribution) also plays a key role in the accuracy and validity of these models.

5 CONCLUSIONS AND FUTURE DIRECTIONS

Simulation has played a key role in AMHS design at Intel and it has become a standard step in the design cycle. Current thinking is in terms of extending the use of simulation to solving additional problems in related areas.

Comparing Model Predictions to Real Systems: As factories ramp up to meet higher production demands, installed systems start operating at ever increasing rates. The teams that designed these systems now have opportunities to see how these systems have been performing and comparing the actual operational performance to the original simulation predictions. Extensive data has been collected and analyzed and model validation completed for most of the large systems. The next challenge is to observe and validate system performance at very high load transfer rates, which will be the true test of the model accuracy.

Linkage to Actual Control Systems: Most systems, especially the Intrabay systems get installed over a period of time. Initially a system might support only a fraction of the equipment set at maturity. How do we test the functionality of these systems? One way to do this is to add equipment emulators and equipment controller emulators. Simulation-validated loading profiles can be used as inputs to these emulators.

We have already taken steps in implementing these ideas in some of the current projects.

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AUTHOR BIOGRAPHIES

GAJANANA NADOLI is a Senior Manufacturing Systems Engineer in the Automated Material Handling Systems Design department at Intel Corporation. He received a B.E. in Mechanical Engineering from the University of Mysore (India), and M.A.Sc. and Ph.D. degrees in Industrial Engineering from the University of Windsor (Canada) and the University of Central Florida, Orlando respectively. His current areas of interests are computer integrated manufacturing, simulation, scheduling systems, object-oriented modeling, and knowledge-based decision support systems.

DEVADAS PILLAI is the Design Engineering Manager for AMHS systems for Intel worldwide. His group is responsible for system concepting, detailed engineering design and simulation analysis, and equipment development of such systems. He has a Bachelor's degree in Mechanical engineering, a Masters degree in Industrial engineering specializing in Computer Aided Processes, and an Masters in Business Administration. He has been at Intel for over 10 years.