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AUTOMATED TRANSPORTATION OF AUXILIARY RESOURCES IN A SEMICONDUCTOR MANUFACTURING FACILITY

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ABSTRACT

In this paper, we study the design of an Automated Guided Vehicle (AGV) transport system for the main auxiliary resource, the mask (also called reticle), in the photolithography area of a semiconductor wafer fabrication facility. We propose two approaches: A static approach based on a simple formula and a dynamic approach relying on a discrete-event simulation model. All the elements of the proposed transport system are characterized. Different layouts and dispatching rules are evaluated and compared using Key Performance Indicators such as the number of performed transport requests, and the assignment and delivery times. Based on these indicators, we show that dispatching rules have a significant impact on the number of required vehicles to perform all the transport requests and that layouts affect the assignment and delivery times. Finally, we have been able to define the adequate transport system that can absorb the transport demand and fits the production environment.

1 INTRODUCTION

In semiconductor manufacturing facilities (fabs), processing a lot of wafers on a machine in the photolithography area (often bottleneck because of the cost of machines) requires an auxiliary resource to be available in the machine. This auxiliary resource, called mask or reticle, is a device used to shape desired geometries on the surface of the wafer. The leverage associated with automated reticle delivery to photolithography process tools may be less apparent than with a fab-wide AMHS (Automated Material Handling System). However, in a high product mix environment, there are thousands of different masks (since one mask is often used in only one process step of only one product) that must be tracked, stored and transported to successfully process wafers on photolithography tools, see (Murray and Miller 2002). The failure to deliver masks in an accurate and timely manner will negate many of the competitive advantages associated with the AMHS. In the 300-mm site of Crolles of STMicroelectronics (called Crolles300 in the sequel), mask deliveries are manually handled by operators using trolleys. But, because of the high mix of products, the number of mask transfers has significantly increased, requiring more people to take care of these transfers. This is why it has been decided that the transport and the handling of masks in the photolithography area had to be automated, in particular because wafers are transported by the AMHS. Two possibilities can be explored: (1) A transport system using the AMHS for wafers (Ben

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Salem *et al.* 2016) with automated vehicles (Overhead Hoist Vehicles) on a rail network in the ceiling of the clean room or (2) A transport system with AGVs on a specific rail network on the floor. The first solution includes vehicles with relatively high speed, with fewer vibrations on the floor and a gain of space on the floor. However, this solution may be expensive and most of the process tools in the photolithography area are incompatible with such a system in Crolles300. The second solution is usually less costly, more flexible and easier to implement. However, it is less fast and takes space on the floor. We decided to study the second solution, because we did not know if the number of mask transport requests could be handled, given the low speed of AGVs and the associated constraining layout. If the second solution does fit the production environment, it is important to characterize it (number of vehicles, layout, vehicle dispatching rule) to deliver the right mask at the right place and at the right time.

Thus, this future AGV transport system must absorb all the mask transport requests, guarantee the productivity of process tools and respond to the variability of semiconductor wafer fabrication. A static approach, based on a simple formula, and a dynamic approach, relying on a discrete-event simulation model, are proposed in this paper.

In the photolithography area of Crolles300, the management of masks is organized as follows: In storage tools, the masks and the pods are separated. When an operator needs a mask from a storage tool, the mask and a pod are associated and brought to the load port of the storage tool. Then, the operator brings the pod to the process tool, the mask is loaded in the machine and the operator puts the empty pod on nearby shelves. The goal is to automate the whole transport and handling process.

The remainder of this paper is organized as follows. In Section 2, a literature survey on different vehicle management rules and layout designs is performed. A simple formula is proposed in Section 3 to define the minimum number of vehicles required to meet the transport demand. A discrete-event simulation model is presented in Section 4, and different scenarios are run to analyze different layouts and different dispatching rules. Some conclusions are drawn in Section 5.

2 LITERATURE REVIEW

AGV design is mainly concerned with the determination of the number of vehicles needed and the dispatching policy.

When examining the determination of the number of vehicles, we can categorize the approaches into three classes: Deterministic, queueing and simulation approaches. The deterministic approaches calculate the number of vehicles necessary to transport lots between tools in an automated material handling system based on either a mathematical programming model or a set of straightforward computations, for example Maxwell and Muckstadt (1982), Egbelu (1987), and Rajotia *et al.* (1998). The required numbers of vehicles are then determined based on the resulting vehicle trips and a ‘from-to’ table, where the frequencies of the transport between the source and destination tools are specified. The queuing approaches use queueing models to determine the number of vehicles, for example Tanchoco *et al* (1987), Nazzal and McGinnis (2007b), and Choobineh *et al.* (2012). These queueing models, although useful, have limitations in practice. They are developed under oversimplified assumptions, for example, the load and unload times are independent of the source and destination tools. The last class of approaches uses discrete event simulation to evaluate the performance of automated material handling systems under different dispatch rules, transport types, number of vehicles and layouts, for example Liao and Fu (2004), Lin *et al.* (2005), Huang *et al.* (2012) and Chang *et al.* (2014). In particular, Liao and Fu (2004) presented a simulation-based, two-phase approach for effective dynamic allocation and dispatching in a 300-mm vehicle system. The objective is to satisfy the transport requirements while minimizing delivery times. When examining the dispatching policy, Kumar (1994) and Li *et al.* (1996) showed that a good dispatching policy significantly improves the performances of a fab. Lu *et al.* (1994) proposed a new class of dispatching rules, (FSVCT-Fluctuation Smoothing for Mean Cycle Time); (fluctuation smoothing policy for variance of cycle time, FSVCT) for minimizing the mean cycle time and for minimizing the variance of cycle time. Hung and Chen (1998) explored a new dispatching rule and a queue prediction dispatching rule for reducing flow times in semiconductor wafer fabrication.

Simulation has often been adopted to evaluate the performance of dispatching rules for rule selection, see for example Lacomme *et al.* (2005). It has the advantages of high fidelity and modeling flexibility in coping with the fast-changing characteristic of wafer fabrications. The benefits of using computer simulation are comprehensively documented in simulation-related publications Banks (2000) and Law *et al.*(1991). Kiba *et al.* (2008) and Ben Chaabane *et al.* (2013) study a balancing strategy of vehicles in the system. This policy, called minimum service policy, is based on the definition of a minimum and maximum number of available vehicles by area.

In this paper, we use simulation to evaluate the right number of vehicles and the right vehicle dispatching policy to transport masks in a dedicated automated transport system.

3 STATIC APPROACH

As already mentioned, in modern fabs, although the transportation of lots of wafers is handled by an AMHS, the transportation of masks is often manually performed. So, to become more efficient and to ensure the reliability of cycle times, it was decided that the transportation of masks should be performed automatically. Hence, our goal is to design a system with AGVs for mask transportation and handling in the photolithography area. Let us first propose a simple formula to determine the minimum number of vehicles required to meet the transport demand. This number is minimal because the formula ignores the time required to go to the demand point and the interaction between vehicles (e.g. congestion and deadlock).

The following notations are introduced:

- T : Time window,
- K : Set of demand points (machine locations),
- V : Number of vehicles required to perform the transport requests,
- T_{ij} : Shortest travel time from point *i* to point *j*,
- R_{ij} : Number of transport requests from point *i* to point *j* during T .

The minimum number of vehicles V can be determined with the following formula:

$$V = \left\lceil \frac{\sum_{ij \in K} R_{ij} T_{ij}}{T} \right\rceil \text{ where } \lceil x \rceil \text{ denotes the smallest integer larger than x.}$$

As an example, if the total time required to perform 1 500 transport requests in a day (1 440 minutes) corresponds to 4 114 minutes of transport times, the number of vehicles $V = \left\lceil \frac{4114}{1440} \right\rceil = 3$. Because the interactions between vehicles and the time spent to go to the demand point are not considered, at least 3 vehicles are necessary.

Although it provides some information to get a crude vision of the potential investment, the static approach is quite limited because, in particular, it does not consider the time spent to go to the demand point and the interactions between vehicles (e.g. congestion, deadlock). This is why we developed a dynamic approach, based on a discrete-event simulation model, to better quantify and characterize the AGV transport system. The model was used to study different elements of the transportation system: Layout, number of vehicles, number and positions of parking locations, vehicle management policy and behavior of the system in case of a peak of transport requests.

4 DISCRETE-EVENT SIMULATION

A discrete-event simulation model requires much more details on the future transport system than with the simple formula of the previous section. Different scenarios of the simulation model using the AutoMod software (see Banks, J. 2000), have been proposed and tested based on the design of the actual 300-mm photolithography area. The photolithography area is a bay that contains machines and mask storage tools to process wafers. Each machine has a load and an unload mask port where vehicles can pick up and deliver masks. For confidentiality reasons, we cannot show the bay configuration. It is designed with an unidirectional monorail where AGVs can transport masks between process and storage tools. The simulation horizon is set to 24 hours, the duration of the warmup period is 30 minutes, the number of independent replications is 110 and a given number of mask transport requests is injected in the model. Each simulation is based on real industrial data, i.e. the actual mask transport requests during one day in the fab considered in this study, and 20 different days have been used, i.e. 20 simulations. Each simulation run takes about 3 minutes. Various layouts and vehicle dispatching policies are compared using Key Performance Indicators (KPIs) such as the number of transport requests and the average and standard deviation of the assignment and delivery times. The numerical results in this section correspond to means and standard deviations of the KPIs on the 20 simulations. Our target is to be able to respond to all transport requests in less than 20 minutes for each request. To reach this goal, we need to define the network layout, the vehicle dispatching rule, how idle vehicles are managed, parking locations, etc.

4.1 Simulating And Comparing Different Layouts

In this section, different layouts are proposed and compared. In the first scenario (see Table 1), vehicle parking locations are located nearby storage tools in order to respond quickly to a transport request starting from storage tools. It is important to note that storage tools are involved in about 70% of mask moves. Vehicles are assigned to a transport request only when they are located in these parking locations. We use the *First Come First Serve* (FCFS) policy to manage the choice of the transport request by a vehicle. Jobs are assigned to the first vehicle that was idle, regardless of its position. Moreover, vehicles have to return to the nearest parking location after a delivery. A unified network is chosen, i.e. in which a vehicle can go from any point to any point, because it requires less storage tools and is more efficient in terms of transport performance than a segregated network, see (Kiba *et al.* 2008). The main characteristics of this configuration are summarized in Table 1 and the results are presented in Table 2. Let us note that, with more than 8 vehicles, all the transport requests are met. Furthermore, Table 2 shows that, with more than 10 vehicles, the standard deviation of the delivery time is about 13 minutes which is acceptable, but the number of vehicles is quite large.

To reduce the number of vehicles, we modify the layout configuration by increasing the number of parking locations and their places are located nearby process tools. Table 3 presents the results of both solutions when the vehicle fleet size varies from 1 to 18.

Table 1: Characteristics of the two different layouts.

Characteristics	**Layout 1**	**Layout 2**
Number of parking locations	8	20
Location	Near *storage* tools	Near *process* tools
Management of idle vehicles	Must return to closest parking location after delivery	Can search another transport request after delivery

Table 2: Simulation results for layout 1.

Number of vehicles	**Percentage of performed jobs**	**Assignment times** (minutes)		**Delivery times** (minutes)	
		Mean	**Stand. dev.**	**Mean**	**Stand. dev.**
1	15%	613.0	993.0	615.0	993.0
2	30%	509.0	818.0	511.0	819.0
4	57%	319.0	505.0	323.0	508.0
6	82%	134.0	215.0	142.0	220.0
8	100%	12.0	19.0	18.0	25.0
10	**100%**	**4.0**	**6.0**	**10.0**	**13.0**
12	100%	2.0	3.0	8.5	12.0
14	97%	1.0	1.5	8.4	11.5
16	95%	0.6	0.4	9.0	12.0
18	95%	0.6	0.6	9.5	13.0

Major improvements are obtained on the number of required vehicles with the number of transport requests and for all KPIs.

- Number of performed transport requests with the size of the vehicle fleet.
  Up to 8 vehicles, increasing the vehicle fleet leads to an increase of the number of performed transport requests. The number of vehicles is too small to cause vehicle congestion. With more than 8 vehicles, all transport requests are met and the number of transport requests remains at 1492 and vehicle congestion is created with more than 12 vehicles.
- Average assignment and delivery times.
  With 8 vehicles, the average delivery time is under 20 minutes. With less than 8 vehicles, the transport system cannot handle all the transport requests, e.g. for 4 vehicles, the average delivery time is about 300 minutes.
  A larger vehicle fleet helps to reduce the assignment time. For example, a decrease of 4.5 minutes is noted when the vehicle fleet increases from 8 to 10 vehicles, and a decrease of 1.4 minutes when the vehicle fleet increases from 10 to 12 vehicles. This is because an idle vehicle is found more quickly with more vehicles.
  A larger vehicle fleet does not necessarily impact the delivery time positively. In fact, an increase of the vehicle fleet may lead to congestion between vehicles, and the delivery time is degraded. In Table 2, a 0.6 minutes increase is noted when the vehicle fleet increases from 14 to 16 vehicles.
  For the same reasons than for the average assignment and delivery times, an increase of the vehicle fleet causes a decrease of the standard deviation of the assignment time and an increase of the standard deviation of the delivery time.
  Thus, a larger vehicle fleet only impacts the assignment time positively, but deteriorates the job delivery time with more than 14 vehicles.
- Standard deviation of assignment and delivery times

From one layout to another, parking locations are added which are located close to process tools. When comparing the first layout to the second one, an improvement of 40% on the standard deviation of the assignment time is noted, and an improvement of 30% on the standard deviation of the delivery time. Hence, with a more appropriate layout, it is possible to gain on both the assignment and delivery times, but the number of vehicles required to perform all the transport requests is not reduced (see Table 3).

Table 3: Comparison of the two layouts.

Number of vehicles	**Percentage of performed jobs**		**Assignment times** (minutes)				**Delivery times** (minutes)			
			Mean		**Stand. dev.**		**Mean**		**Stand. dev.**	
	Layout 1	Layout 2	Layout 1	Layout 2	Layout 1	Layout 2	Layout 1	Layout 2	Layout 1	Layout 2
1	15%	16%	613.0	605.0	993.0	974.0	615.0	607.0	993.0	975.0
2	30%	32%	509.0	497.0	818.0	801.0	511.0	500.0	819.0	802.0
4	57%	60%	319.0	293.0	505.0	483.0	323.0	297.0	508.0	486.0
6	82%	86%	134.0	105.0	215.0	162.0	142.0	110.0	220.0	166.0
8	100%	**100%**	12.0	**7.0**	19.0	**12.0**	18.0	**13.0**	25.0	**18.0**
10	100%	100%	4.0	3.0	6.0	4.0	10.0	9.0	13.0	12.0
12	100%	100%	2.0	1.0	3.0	2.0	8.5	8.0	12.0	11.0
14	97%	99%	1.0	0.6	1.5	0.6	8.4	8.0	11.5	11.0
16	95%	99%	0.6	0.4	0.4	0.1	9.0	9.0	12.0	12.0
18	95%	99%	0.6	0.4	0.6	0.0	9.5	10	13.0	15.0

4.2 Simulating And Comparing Different Dispatching Rules

Vehicle dispatching policies aim at quickly answering transport requests by selecting a transport request from those that are available, and assigning it to an available vehicle. The dispatch is triggered in the three following cases:

1. Right after a delivery (the vehicle becomes available),
2. When a vehicle enters a parking location,
3. And when there is a new transport request.

A dispatching rule tries to minimize the waiting time of lots, i.e. the queue length of waiting transport requests, to maximize system productivity and to ensure the right service level for each machine. Different vehicle dispatching rules are considered and compared in the simulation model. The main one are listed below:

- ***First Come First Serve*** (FCFS). The vehicle is assigned to the transport request that has been waiting the longest.
- ***Nearest Vehicle*** (NV). As soon as a transport request is created, the distance criterion is evaluated between idle vehicles and the departure point of the transport request. The selected vehicle is the one which is the closest. A variant of this policy takes into account vehicle speed (temporal proximity). In this case the selected vehicle is the one that takes less time. This rule thus minimizes travel distance of empty vehicles because it selects the pair (vehicle, departure point) with the smallest pick-up time.

- ***Shortest Travel Distance*** (STD). The selected transport request is the one which is the closest to the vehicle in terms of time or travel distance.

Based on these vehicle dispatching policies, we propose different realistic scenarios:

- Scenario 1: FCFS
    - Scenario 1_1: In addition to the FCFS policy, vehicles return to parking locations after each delivery.
    - Scenario 1_2: In addition to the FCFS policy, vehicles do not need to return to parking locations after each delivery.
- Scenario 2: NV
- Scenario 3: FCFS combined with NV (FCFS + NV). As soon as a transport request is created, the distance criterion is evaluated between idle vehicles and the departure point of the transport request. The selected vehicle is the one which is the closest. If any vehicle is found, the transport request is assigned to the first idle vehicle in the system, regardless of its position.
- Scenario 4: STD-12m combined with FCFS (STD-12m + FCFS). An idle vehicle searches for transport requests at all locations sorted by distance from the current location of the vehicle, ignoring locations farther than 12 meters. If several transport requests are found, the vehicle is assigned to the one that has been waiting the longest.
- Scenario 5: STD-48m combined with FCFS (STD-48m + FCFS). Same as scenario 4 but vehicles ignore locations farther than 48 meters.
- Scenario 6: Scenario 4 combined with mask/pod dissociation, i.e. any empty pod can be used to unload a mask from a process tool (decrease of unloading time).
- Scenario 7: Scenario 6 combined with layout 2.

The simulation results of scenario 1_1 and scenario 1_2 are presented in Table 4. All transport requests are performed with at least 7 vehicles for both scenarios. Improvements are observed for assignment and delivery times in scenario 1_2. More precisely, 2 minutes is gained on the average assignment time and 1 minute on the average delivery time, but the minimum number of required vehicles remains the same (at least 7 vehicles). Hence, additional improvements are required to reduce the vehicle fleet size.

Table 4: Two scenarios with different types of dispatching rules.

Number of vehicles	**Percentage of performed jobs**		**Assignment times** (minutes)				**Delivery times** (minutes)			
			Mean		**Stand. dev.**		**Mean**		**Stand. dev.**	
	Scenario 1_1	Scenario 1_2	Scenario 1_1	Scenario 1_2	Scenario 1_1	Scenario 1_2	Scenario 1_1	Scenario 1_2	Scenario 1_1	Scenario 1_2
7	100%	100%	24.0	12.0	36.0	19.0	30.0	18.0	40.0	25.0
8	100%	100%	7.0	**5.0**	12.0	**10.0**	13.0	**12.0**	18.0	**17.0**

Different scenarios are tested and presented in Table 5:

- *In scenario 2*, 12 vehicles are required to answer the transport demand and the average delivery time to the machines is 18 minutes. When some departure and arrival points are more popular than others, the system becomes unbalanced because the number of vehicles increases at some points and decreases at others. Since the NV policy used in scenario 2 is based on the proximity of vehicles and departure points, some transport requests are not performed (vehicles are too far).

- *In scenario 3*, the FCFS rule is added as a second option to the NV rule. The minimum number of required vehicles to perform all the transport requests is reduced to 6 compared to 12 for the NV rule. This improvement is due to the FCFS policy that allows the transport system to answer the transport demand even if vehicles are far from departure points.
- *In scenario 4*, the STD-12m + FCFS rule is applied. Significant improvements are observed, mainly on the vehicle fleet size required to meet all the transport requests: 5 vehicles instead of 8 vehicles for scenario 1_2. Delivery and assignment times are reduced, e.g. the average delivery time is 8.7 minutes.
- *In scenario 5*, the STD-48m + FCFS rule is used where the vehicle search range is increased. Significant improvements are observed on the required vehicle fleet size compared to scenario 1_2 but scenario 4 remains the best for the average delivery time (8.7 minutes versus 9.4 minutes).

Table 5: Means and standard deviations of delivery times, vehicle utilization rates and vehicle idle times for different scenarios.

Dispatching rules	**Minimum required vehicles**	**Delivery times** (minutes)		**Vehicles**	
		Mean	**Stand. dev.**	**Utilization**	**Idle time**
Scenario 1_2	8	12.0	17.0	83%	17%
Scenario 2	12	18.0	135.6	72%	28%
Scenario 3	6	9.2	16.1	79%	21%
Scenario 4	5	8.7	18.6	78%	22%
Scenario 5	5	9.4	17.0	80%	20%
Scenario 6	4	6.0	12.2	67%	33%
Scenario 7	**4**	**5.5**	**9.7**	62%	38%

- *In scenario 6*, a change is made on the way masks are monitored in the photolithography area. When they are removed from storage tools, masks are associated with specific pods to make their identification easier, so a given mask is always linked with its pod. The consequence of this is that a mask can only be picked up by its corresponding pod after it is released from a process tool. Therefore, by avoiding this mask/pod association, mask loading and unloading times can be gained. The required size of the vehicle fleet is reduced to 4 vehicles, i.e. a gain of one vehicle compared to scenarios 4 and 5. All the other improvements affect the assignment or delivery times. A change of dispatching rule always impacts the minimum required number of vehicles and other changes related to the layout or to the parking locations only impact times (see Table 1 for information about the characteristics of layouts).
- *In scenario 7*, a combination of the best layout and the best dispatching rule found so far are used. The minimum required number of vehicles remains 4 but the average delivery time drops to 5.5 minutes.

Up to this point, all the indicators were related to mask deliveries (number of masks delivered on time). Indicators on the management of the vehicles are presented in Table 5. Note that, from scenario 1_2 to scenario 5 for which mask/pod association is considered, the utilization rate of the vehicles is between 72% and 83% against 67% and 62% for scenarios 6 and 7 (where masks and pods are dissociated). Thus, vehicles are used more efficiently in scenarios 6 and 7 than in the other scenarios.

Other cases were also analyzed for industrial purposes. For instance, we studied what is the required number of vehicles if we want 80% (case 1), 95% (case 2) or 100% (case 3) of the transport requests to be performed under 20 minutes. Moreover, the battery life of vehicles and their down times for maintenance were taken into account in the simulation model. The results showed that scenario 7 is still the best one and that 7 vehicles are required in case 1, 9 in case 2 and 10 in case 3.

5 CONCLUSION

This paper aims at defining an appropriate mask transport and handling system for the photolithography area in semiconductor manufacturing facilities. An AGV transport system is defined by a layout, a number of vehicles, a number of parking areas and a vehicle management policy. A simple formula is initially used to determine the minimum required number of vehicles. Then, we proposed a discrete-event simulation model to evaluate different layouts and vehicle dispatching rules. and we find out that the *Shortest Travel Distance* rule outperforms the other dispatching rules that we analyzed. At the beginning, 8 vehicles are necessary to meet the transport demand but with some high optimization, we were able to reduce this number to 4 vehicles. Nevertheless, optimizations that we can make reduce the number of vehicles but will add some costs during the implementation phase. It means that costs are saved by reducing the number of vehicles are lost during implementation phase on software aspects.

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