A Study on Storage Allocation in an Automated Semiconductor Manufacturing Facility

Stéphane Dauzère-Pérès, Claude Yugma, Ahmed Ben Chaabane
Department of Manufacturing Sciences and Logistics, Ecole des Mines de Saint-Etienne, CMP Georges Charpak
F-13541 Gardanne, France
Dauzere-Peres@emse.fr, Yugma@emse.fr, Benchaabane@emse.fr

Lionel Rullière, Gilles Lamiable
Department of Industrial Engineering
STMicroelectronics
F-38926 Crolles, France
Ahmed.Ben-Chaabane@st.com, Lionel.Rulliere@st.com, Gilles.Lamiable@st.com

Abstract

This paper deals with the allocation of storage capacity in the automated material handling environment of a semiconductor wafer manufacturing facility. The impact of the allocation of stockers to machines in semiconductor fabrication facilities (fabs) is very little studied, although it significantly impacts the efficiency of the Automated Material Handling System (AMHS). After motivating and describing the problem of allocating unitary stockers to machines, a first local approach is discussed. We then propose a Mixed Integer linear Programming model to solve the global problem with two objectives: Minimizing the total maximum travel distance of vehicles and balancing the utilization of unitary stockers. Based on real data, numerical experiments are performed on some small instances. The analysis shows the importance of some parameters and that the two objectives tend to conflict.

1 Introduction

In modern 300mm semiconductor wafer manufacturing facilities (wafer fabs), material handling is more and more automated to improve manufacturing efficiency and increase the overall factory effectiveness. Automated Material Handling Systems (AMHSs) in wafer fabs aim at optimizing productivity ([10]) and can be classified in three types: (1) Interbay, where vehicles transport lots (cassettes with at most 25 wafers) between process bays, (2) Intrabay, where lots are transported between machines in the same bay, and (3) Unified, where vehicles can transport lots from anywhere to anywhere in the fab and avoid using intermediate stockers. In a non-unified system, when a lot has to go from point A to point B that are in different bays, a vehicle carries the lot from point A to an exit stocker (intrabay), then another vehicle carries the lot from the exit stocker to the entrance stocker of the bay of point B (interbay), and finally a third vehicle carries the lot from the entrance stocker to point B (interbay). In a unified system, a single vehicle can bring the lot from A to B. If B corresponds to a machine and all load ports of this machine are occupied, then the lot is placed in a stocker.

In interbay systems, vehicles usually move material using a monorail and interface with AS/RS machines (stockers) in bay areas where materials are processed. The most practical approach to enhance the performance of interbay AMHSs is to minimize the travel distances between stockers by using a custom track layout with turntables. Kurosaki et al. [6] and Pillai et al. [11] address the linking of interbay and intrabay track options of a 300mm fab layout. They found that the delivery time of isolated and linking track systems is highly dependent on the traffic type. Cardarelli and Pelagagge [1] use discrete-event simulation to examine the system performance with factors such as stocker capacity, production planning and scheduling, and system management. They showed that the storage capacity distribution along the interbay track is important in maintaining the hallway performance. Mackulak et al. [7] investigate the relationship between the vehicle carrying capacity and the tool batch size of an intrabay system. The results show that vehicle capacity has the most significant effect on average delivery time.

In modern automated fabs, unitary stockers (or Overhead Hoist Buffers, OHBs) are used at the ceiling above machines to guarantee fast access when storing and, most importantly, retrieving a lot. Because the number of OHBs is limited and cannot cover the total required storage capacity, big stockers with large storage capacity (several hundreds lots) are still necessary. In most cases, using OHBs helps to strongly decrease the transport time of a lot to a machine compared to big stockers. The AMHS brings lots from and to machines either from OHBs or big stockers. Each machine is associated to a group of OHBs, called default stocker, where lots that the machine can process are brought before the machine is available to process these lots. Actually all machines of the same type, i.e. that can perform the same operations, are associated to the same default stocker. This is because, when a lot is stored to wait for a given operation, the actual machine that will perform the operation among the set of possible machines is not known. In practice, each machine has not only a default stocker, but also a list of "alternates", i.e. other storage possibilities in case all OHBs of the default stocker are full.

In this paper, we are interested in determining the default stockers and their association to machines. Oversizing default stockers leads to under usage of storage resources, while undersizing default stockers leads to lots being too often directed towards alternates which are often big stockers. Preliminary studies were conducted with discrete event simulation in [5]. The introduction of OHBs improves the performance of the AMHS, essentially the delivery time of lots to machines. In a standard fab, the number of OHBs can be larger than one thousand. Managing the assignment of OHBs is complex. This is due to various constraints and to the variability in how the OHBs are used, in particular because of the dynamics of the AMHS such as the availability of vehicles. The unbalance of the system can be explained by various reasons, including:

- The fact that machines in the same family are not in the same bay (this causes a division of flows and leads to multiples ways to dispatch a lot intended to be processed on these machines),
- And the absence of a decision support tool to update the number of OHBs dedicated to machines due to flow or product mix changes.

In the literature, there are few articles dealing with the location of stockers (in particular OHBs) and their assignment to machines. Researchers are mainly studying big stockers, which are essentially used in inter-bay zones and are potential bottlenecks of the system. As a result, simulation studies such as the one in Cardarelli and Pelagagge [1] were performed to find the optimal dimension of stockers and to determine a balance between production and the passage of lots through each area. In addition, the layout of stockers is the priority of these studies: Policies are tested to get the best solution for the storage system such as distributed and centralized layouts (see [8] and [9]). Kiba et al. [5] studied a real AMHS by simulation, where the interaction between transportation, production and storage is analyzed. Today, unitary stockers (OHBs) are direct suppliers of machines. Placed either at one or at both sides of the rail, OHBs have the advantage of a faster access compared to a stocker, which is equipped with an inside track-robot to manage the entrance and the exit of lots. Some studies deal with the hardware design of AMHS. Han et al. [3] describe two settings: The Dual Unified OHT (Overhead Hoist Transfer) system (DUO) and the Single Unified OHT System (SUO). These settings concern the interaction between vehicles and OHBs. Simulations were done to show the interest of each design.

This paper aims at investigating the definition of groups (*default stockers*) of unitary stockers (OHBs) and the association of these groups to machines and analyzing the impact on some performance indicators in a unified 300 mm fab. The paper is organized as follows. Section 2 discusses the impact of the location and sizing of stockers on the AMHS performances indicators. Section 3 presents the first approach we developed to manage OHBs, whose main drawback is its local vision since only machines performing the same processes are considered. This is why we propose a Mixed Integer Linear Program (MILP) in Section 4. The MILP aims at globally assigning each OHB to one group and associating one group of OHBs to each machine. Numerical experiments on data from an actual fab are conducted in Section 5. Some conclusions and perspectives can be found in Section 6.

2 Impact of storage decisions in semiconductor manufacturing facilities

Storage is a primordial stake in modern semiconductor fabs because its management may affect productivity. Indeed, the positions of stockers and their sizing directly impact the time required to bring lots to machines. This was clearly shown by simulation in the work of Kiba et al. [5]. Not only production, but also transport and storage are key elements of productivity. Jimenez et al. [4] present a decision rule that selects the rail with the minimum travel distance between source and destination stockers in a non-unified fab, and its performance is evaluated using discrete event simulation. In the literature, storage is often treated as a "simple" intermediary between transport and production. This is particularly true in transportation systems with inter-bay/intra-bay configurations [2], because stockers are the only means of exchange between areas. Table 1 summarizes some important articles on storage problems in semiconductor manufacturing facilities.

Authors	**Year**	**Subject**
Cardarelli and Pelagagge [1]	1995	Interaction between transport, production and storage
Pillai et al. [11]	1999	Relation between stockers, rails and number of vehicles
Mackulak and Savory [8]	2001	Distributed vs. Centralized management
Wiethoff and Swearingen [13]	2006	Integrating production rules in stocker management

Table 1: Research on storage problems in semiconductor manufacturing facilities

In Mackulak and Savory [8], the impact of the number of trips per hour of vehicles, the use of the stockers and the average delivery times on different configurations of the storage system (distributed or centralized) are studied. Simulation results show that the average delivery time in the distributed system is better than in the centralized system. The utilization rate of the interior robot to the storekeeper varies from 24.0% to 38.4% for distributed systems, and from 17% to 52% for centralized systems. The article concludes that distributed systems are better than centralized systems. This illustrates that storage impacts transport and production.

In Pillai et al. [11], the optimal location of stockers in several rail configurations are studied. As storage space is an important element in the total cost of the AMHS, it is preferable to select the configuration using the least amount of storage areas.

Cardarelli and Pelagagge [1] worked on the design and the optimization of inter-bay systems and storage using probabilistic methods. If a lot is in the stocker, removing the lot from the stocker depends on the cycle time of the robot and the availability of the external load port. The use of the robot in the stocker and the use of the external port depend on the availability of operators. In other cases, the removal of the lot depends on traffic. The authors concluded that it was difficult with these methods to achieve significant results on the capture of dynamic aspects (availability of ports, traffic density, etc.). This study illustrates again the interaction between transport, production and storage and, moreover, that this interaction is not obvious to manage.

Hence, although storage in AMHS has not been thoroughly studied in the literature, it is an essential element of fab productivity.

3 A Local Approach for Analyzing Storage Allocation

The local approach consists in using center-of-gravity calculations to detect abnormalities in the current storage allocation. Thus, it is necessary to determine the distances between the positions of possible stockers and the positions of machines. We first had to define a system of points in the fab: X_i, $i \in \{1 \dots n\}$, where X_i represents a machine or an eventual storage place. To use center of gravity, it is necessary to calculate the distance between each couple of points. We collected the available data in the control system of the AMHS to construct the matrix of distances. The way the fab is structured for the AMHS is based on points and distances. Each point may represent a load port of a machine, an OHB or a theoretical point on the rail. The control system of the AMHS contains map data that guide vehicles. Each point has an IDentification (ID) and one or two out segments. Each segment has an ID, one terminal point and a length. Once data are available, we can construct the distance matrix with the Floyd-Warshall algorithm [12] to get the shortest distance between each pair of points in the fab.

In a semiconductor manufacturing facility, machines are qualified with different types of processes. Each lot follows a logical route with an average of six hundred steps. This route is characterized with re-entrant flows and so a lot may visit the same machine many times. This makes it difficult to identify machines with the same processes. Our first approach is to group equipment on the basis of one common process and avoid processes qualified for inventory and non-productive lots. This decision allows us to form global groups of machines.

The objective is to determine the weight of each OHB and to make a ranking for detecting any unbalance in the storage allocation system. This ranking allows us to detect the variability of using some OHBs to serve machines. Using the activity, i.e. the number of transports to each machine (A_m) $m \in \{1 \dots M\}$, we can find the center of gravity of each group of M machines. To balance the activity of the machines in the group and the distance of each stocker to reach these machines, the following weight is used:

$$Weight_i = \frac{\sum_{m=1}^{M} d_{i,m} a_m}{\sum_{m=1}^{M} a_m}$$

where $d_{i,m}$ is the shortest distance between stocker i and machine m, and a_m is the activity of machine m, i.e. the number of transports to machine m.

The approach allows us to rank and compare the actual setting and the proposed one obtained using center-of-gravity calculations. Table 2 shows an example for six OHBs. One can notice that the first three OHBs (OHB1, OHB2 and OHB3) in the actual setting of the fab are the same than the ones in the proposed setting determined by the local approach. For the last three stockers, the proposed OHBs are different. The values of Δ indicate the difference between the weights of the OHBs in the actual setting and the proposed setting.

This simple method does not take into account the overall vision of the fab. In particular, an OHB is not actually linked to a machine but is assigned to a group (default stocker)

Actual setting		Proposed setting		Δ
OHB	Weights	OHB	Weights	
OHB1	47	OHB1	47	0
OHB2	48	OHB2	48	0
OHB3	48	OHB3	48	0
OHB20	67	OHB80	57	10
OHB21	68	OHB81	57	11
OHB22	73	OHB82	57	16

Table 2: Comparison between actual ranking and proposed ranking.

which is associated to machines. This is why we propose in the following section a more global approach.

4 A Mixed Integer Linear Program for Optimizing Storage Allocation

This section presents a Mixed Integer Linear Programming (MILP) model for allocating unitary stockers (OHBs or bins) to machines in a unified fab. Groups of bins are created and associated to machines with two objectives: Minimizing the maximum travel distances from bins to machines and minimizing the maximum bin utilization.

The parameters of the MILP model are:

B: Number of bins (OHBs),
M: Number of machines,
G: Maximum number of groups of bins (default stockers) to be created,
$d_{i,m}$: Travel distance (or time) between bin i and machine m,
a_m: Activity of (number of transports to) machine m,
u_m: Utilization of stockers for machine m (can also be seen as the necessary size of queue for machine m).

The decisions variables are:

$X_{i,g} = 1$ if bin i is assigned to group g, and 0 otherwise,
$Y_{m,g} = 1$ if machine m is associated to group g, 0 otherwise,
TT: Total maximum travel distance (or time) for all machines,
TT_m: Maximum travel distance (or time) for machine m,
MU: Maximum utilization of a bin,
$UU_{m,i,g}$: Utilization of bin i for machine m in group g.

Our MILP model is written below:

$$\sum_{g=1}^{G} X_{i,g} = 1 \qquad \forall i = 1 \dots B \tag{1}$$

$$\sum_{g=1}^{G} Y_{m,g} = 1 \qquad \forall m = 1 \dots M \tag{2}$$

$$TT_m \geq d_{i,m} a_m (X_{i,g} + Y_{m,g} - 1) \qquad \forall m = 1 \dots M, \forall i = 1 \dots B \tag{3}$$

$$TT = \sum_{m=1}^{M} TT_m \tag{4}$$

$$X_{i,g} \leq \sum_{m=1}^{M} Y_{m,g} \qquad \forall i = 1 \dots B, \forall g = 1 \dots G \tag{5}$$

$$\sum_{i=1}^{B} \sum_{g=1}^{G} UU_{m,i,g} = u_m \qquad \forall m = 1 \dots M \tag{6}$$

$$UU_{m,i,g} \leq u_m X_{i,g} \qquad \forall i = 1 \dots B, \forall g = 1 \dots G, \forall m = 1 \dots M \tag{7}$$

$$UU_{m,i,g} \leq u_m Y_{m,g} \qquad \forall i = 1 \dots B, \forall g = 1 \dots G, \forall m = 1 \dots M \tag{8}$$

$$MU \geq \sum_{m=1}^{M} UU_{m,i,g} \qquad \forall i = 1 \dots B, \forall g = 1 \dots G \tag{9}$$

$$X_{i,g} \in \{0,1\} \qquad \forall i = 1 \dots B, \forall g = 1 \dots G \tag{10}$$

$$Y_{m,g} \in \{0,1\} \qquad \forall m = 1 \dots M, \forall g = 1 \dots G \tag{11}$$

Constraint (1) ensures that each bin is assigned to one and only one group of bins and Constraint (2) that each machine is associated to one and only one group of bins. Constraint (3) is used to determine the maximum travel distance (or time) TT_m for machine m. Note that it corresponds to the travel distance (or time) from the bin i assigned to machine m (or similarly to the group associated to m) which is the furthest from machine m weighted by the activity of machine m. Constraint (4) helps to determine the total maximum travel distance for all machines. Constraint (5) imposes that a bin is only assigned to a group if there is at least one machine associated to the group. This constraint is necessary since, when the minimization of TT is emphasized, it would be optimal to put bins that are the furthest from the machines in a "shadow" group with no machine associated. Constraint (6) indicates that the sum of the utilizations of bins in groups for a given machine m is equal to the required utilization u_m of stockers for machine m. Constraints (7) and (8) ensure that the utilization $UU_{m,i,g}$ of bin i for machine m in group g is only strictly positive if bin i is in group g (i.e. $X_{i,g} = 1$) and machine m is in group g (i.e. $Y_{m,g} = 1$). Constraint (9) is used to determine the maximum utilization of a bin by a machine. Constraints (10) and (11) impose that $X_{i,g}$ and $Y_{m,g}$ are binary variables.

The bi-objective function (12) aims at minimizing the travel distance (or time) while balancing the utilization of bins, where α and β are weighting parameters.

$$Min \quad \alpha TT + \beta MU \tag{12}$$

As illustrated in the numerical experiments of the following section, the two objectives tend to diverge. This is because, when minimizing TT, more groups are likely to be created with few bins that are close to machines and thus balancing the utilization of bins is not optimal. On the other hand, balancing the utilization of bins is optimal when only one group is created, since all machines can share all bins.

It is well-known that Constraint (3) leads to very poor linear relaxations, thus making the use of standard mathematical programming solvers difficult. To improve the model, we introduce a new binary variable $YY_{i,m,g}$ which is equal to 1 if both bin i is assigned to group g and machine m is associated to g, and 0 otherwise. Constraints (3), (5), (7), (8) and (9) are deleted and the following constraints are added in the model:

$$YY_{i,m,g} \leq X_{i,g} \quad \forall i = 1 \ldots B, \forall m = 1 \ldots M, \forall g = 1 \ldots G \tag{13}$$

$$YY_{i,m,g} \leq Y_{m,g} \quad \forall i = 1 \ldots B, \forall m = 1 \ldots M, \forall g = 1 \ldots G \tag{14}$$

$$TT_m \geq d_{i,m} a_m YY_{i,m,g} \quad \forall m = 1 \ldots M, \forall i = 1 \ldots B \tag{15}$$

$$X_{i,g} \leq \sum_{m=1}^{M} YY_{i,m,g} \quad \forall i = 1 \ldots B, \forall g = 1 \ldots G \tag{16}$$

$$UU_{m,i,g} \leq u_m YY_{i,m,g} \quad \forall i = 1 \ldots B, \forall g = 1 \ldots G, \forall m = 1 \ldots M \tag{17}$$

$$MU \geq \sum_{m=1}^{M} \sum_{g=1}^{G} UU_{m,i,g} \quad \forall i = 1 \ldots B \tag{18}$$

$$YY_{i,m,g} \in \{0,1\} \quad \forall i = 1 \ldots B, \forall m = 1 \ldots M, \forall g = 1 \ldots G \tag{19}$$

Constraints (13) and (14) replace Constraints (7) and (8), and ensure that $YY_{i,m,g}$ is equal to 1 only if $X_{i,g} = 1$ (i.e. bin i is assigned to group g) and $Y_{m,g} = 1$ (i.e. machine m is associated to group g). Constraint (15) is stronger than Constraint (3) for the calculation of the maximum travel distance for machine m. Constraint (16) is equivalent to Constraint (5) and guarantees that a bin is not assigned to a group with no machine. Constraint (17) is equivalent to Constraints (7) and (8). Constraint (18) is stronger than Constraint (9). Constraint (19) imposes that $YY_{i,m,g}$ is a binary variable.

An additional cut was introduced to remove part of the symmetry related to the solutions of the model:

$$\sum_{g=1;\ g>m}^{G} Y_{m,g} = 0 \qquad \forall m = 1 \ldots M \tag{20}$$

Constraint (20) forces machine 1 to be associated to group 1, machine 2 to be associated to groups 1 or 2 and so on. Other cuts were added but were not found to be very effective in our numerical experiments.

Faster and better results were obtained with this reformulation. However, only relatively small instances could be solved in an hour of computational time as shown in the next section. We were not able to find good solutions for instances with 20 machines and 60 bins.

5 Numerical experiments

To test the mathematical programming model, one instance type was considered and solved with the standard solver IBM ILOG CPLEX 12.3 in a maximum computational time of one hour on a 2.8 GHz PC with 12 GB and 8 processors. The instance includes 10 machines and 30 bins, and the maximum number of groups was varied. The distances between machines and bins, the activities of machines and the utilizations of stockers by machines are taken from actual fab data. Solving larger instances was not possible in a reasonable amount of time. Since the semiconductor manufacturing facility we are studying includes more than 300 machines and 1,000 bins, dedicated heuristics need to be developed to solve real-life instances.

Table 3 shows the results when varying the maximum number of groups of bins G and when the total maximum travel distance (TT) is prioritized over the maximum utilization of a bin (MU) by using the objective function $TT+MU$. The optimal solution is found in all cases. As discussed earlier, TT decreases when G increases up to 8 groups. When G is equal to 9 or 10, only 8 groups are created since TT cannot be improved and having less groups helps to reduce MU. As expected, the smallest MU is obtained when $G = 1$. However, note that MU is not increasing with the allowed number of groups of bins, and depends on the instance.

G	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
MU	0.167	4.5	3.5	2	2	1	1	1	1	1
TT	13 960	2 832	2 076	1 536	1 179	1 007	915	887	887	887

Table 3: Results for different values of G when $TT+MU$ is minimized (optimal solution found in all cases).

Table 4 shows the results when the maximum utilization of a bin (MU) is prioritized over the total maximum travel distance (TT) by using the objective function $TT+$ 100,000 MU. The optimal solution is not always found or at least proved optimal. This is why gaps to optimality are also provided. As expected, MU always remains to its minimal value for all values of G. Actually, in this instance, it is possible to always reduce TT by increasing G while keeping MU to its minimal value.

G	1	2	3	4	5	6	7	8	9	10
MU	0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167
TT	13 960	6 688	4 978	4 199	3 173	2 548	2 563	2 060	2 087	1 985
Gap (%)	0.00	0.18	1.35	1.86	1.43	1.09	1.13	0.77	0.73	0.62

Table 4: Results for different values of G when $TT+$ 100,000 MU is minimized.

6 Conclusion and perspectives

In this paper, we dealt with the problem of optimally allocating unitary storage capacity to machines in the Automated Material Handling System of a unified semiconductor wafer manufacturing facility. We proposed a Mixed Integer Linear Programming (MILP) model to solve this problem. The objective is to minimize the total maximum travel distance (or time) for all machines, and the maximum utilization of unitary stockers (OHBs or bins).

Some computational experiments were conducted, which illustrate the impact of the allocation of OHBs on the objectives. Since there are usually more than 300 machines and 1,000 OHBs in a real semiconductor manufacturing facility, the proposed MILP cannot be directly used to solve industrial instances with a standard solver. This is why we are working on the development of dedicated heuristics. In addition, various additional industrial constraints must be considered such as, for example, the fact that some OHBs must be grouped together or that some OHBs are dedicated to specific machines.

References

[1] E. Cardarelli and P. M. Pelagagge. Simulation tool for design and management optimization of automated inter bay material handling and storage systems for large wafer fab. *IEEE Transactions on Semiconductor Manufacturing*, 8(1):44–49, 1995.

[2] G. Gaxiola and L. Hennessy. Evaluation of advantages of integrating 300mm amhs fab layout in the photo area. In *Proceedings of the 2001 IEEE International Symposium of Semiconductor Manufacturing, ISSM*, pages 373–376, San Jose, CA, USA, October 08-10, 2001.

[3] C. Han, K. Pare, M. Tokumoto, and A. Aoki. High throughput amhs design with dual unified oht system. In *Proceedings of the 2011 International Symposium on Semiconductor Manufacturing*, pages 185–188, Tokyo, Japan, 05-07 September, 2011.

[4] J. Jimenez, B. Kim, J. Fowler, G. Mackulak, and Y. I. Choung. Operational modeling and simulation of an inter-bay amhs in semiconductor wafer fabrication. In *Proceedings of the 2002 Winter Simulation Conference*, pages 1377–1382, San Diego, California, USA, 8-11 December, 2002.

[5] J.-E. Kiba, S. Dauzère-Pérès, C. Yugma, and G. Lamiable. Simulation of a full 300mm semiconductor manufacturing plant with material handling constraints. In *Proceedings of the 2009 Winter Simulation Conference 2009*, pages 1601–1609, Austin, Texas, USA, December 13-16, 2009.

[6] R. Kurosaki, N. Nagao, H. Komada, Y. Watanabe, and H. Yano. Amhs for 300mm wafer. In *Proceedings of IEEE International Symposium on Semiconductor Manufacturing Conference*, pages 13–16, San Francisco, USA, 6-8 October, 1997.

[7] G. T. Mackulak, F. P. Lawrence, and J. Rayter. Simulation analysis of 300mm intrabay automation vehicle capacity alternatives. In *Proceedings of 1998 Semiconductor Manufacturing Conference*, pages 445–450, Boston, USA, 1998.

[8] G. T. Mackulak and P. Savory. A simulation-based experiment for comparing amhs performance in a semiconductor fabrication facility. *IEEE Transactions on Semiconductor Manufacturing*, 14(3):273–280, 2001.

[9] L. Miller, A. Bradley, A. Tish, T. Jin, J.-E. Jimenez, and R. Wright. Simulating conveyor-based amhs layout configurations in small wafer lot manufacturing environments. In *Proceedings of the 2011 Winter Simulation Conference*, pages 1939–1947, Phoenix, USA, 11-14 December, 2011.

[10] G. Nadoli and D. Pollai. Simulation in automated material handling systems design for semiconductor manufacturing. In *Proceedings of the 1994 Winter Simulation Conference*, pages 892–899, Lake Buena Vista, USA, 11-14 December, 1994.

[11] D. Pillai, T. Quinn, K. Kryder, and D. Charlson. Integration of 300mm fab layouts and material handling automation. In *Proceedings of IEEE/CHMT Ninth International Electronic Manufacturing Technology Symposium*, pages 23–26, Santa Clara, USA, 11-13 October, 1999.

[12] S.Warshall. A theorem on boolean matrices. *Journal of ACM*, 9:11–12, 1962.

[13] T. Wiethoff and C. Swearingen. Amhs software solutions to increase manufacturing system performance. In *Proceedings of the 2006 IEEE/SEMI Advanced Semiconductor Manufacturing Conference*, Boston, Massachusetts, USA, 22-24 May, 2006.