Proceedings of the 2008 Winter Simulation Conference
S. J. Mason, R. R. Hill, L. Mönch, O. Rose, T. Jefferson, J. W. Fowler eds.

AN ANALYTICAL MODEL FOR CONVEYOR BASED AMHS IN SEMICONDUCTOR WAFER FABS

Dima Nazzal

4000 Central Florida Blvd.
Department of Industrial Engineering and Management Systems
University of Central Florida
Orlando, FL 32816, U.S.A.

Andrew Johnson

237K Zachry Engineering Center
Department of Industrial and Systems Engineering
Texas A&M University
College Station, Texas 77843-3131 U.S.A.

Hector J. Carlo

P.O. Box 9043
Department of Industrial Engineering
University of Puerto Rico-Mayagüez
Mayagüez, PR 00681, U.S.A.

Jesus A. Jimenez

Ingram School of Engineering
Texas State University-San Marcos
San Marcos, TX 78660-4616, U.S.A.

ABSTRACT

This paper proposes an analytical model useful in the design of conveyor-based Automated Material Handling Systems (AMHS) to support semiconductor manufacturing. The objective is to correctly estimate the work-in-process on the conveyor and assess the system stability. The analysis approach is based on a queuing model, but takes into account details of the operation of the AMHS including turntables. A numerical example is provided to demonstrate and validate the queuing model over a wide range of operating scenarios. The results indicated that the analytical model estimates the expected work-in-process on the conveyor with reasonable accuracy.

1 INTRODUCTION

Driven by Moore's Law, semiconductor wafer manufacturers are constantly seeking opportunities to improve productivity while reducing costs and cycle times within their wafer fabrication facilities (fabs). Because effective material handling practices are significant contributors to reduced wafer cycle times, there is a need to streamline the design and operations of the Automated Material Handling System (AMHS).

The problem is that most traditional 300mm wafer fabs are highly complex (with hundreds of processing steps), and have high throughput requirements (over 20,000 wafer starts per month). As a result, the existing AMHS technology operating in a 300mm wafer fab is facing the following challenges:

1. To reduce wafer cycle time average and standard deviation while processing larger amounts of move transactions.
2. To maximize process tool uptimes while rapidly responding to highly dynamic, highly variable processing events, i.e. first wafer effects, high product mix, high fluctuations in demand, several different lot priorities, unscheduled tool breakdowns, etc.
3. To minimize work-in process (WIP), and possibly minimize the use of centralized storage units (stockers).
4. To travel longer distances within the fab, and perform deliveries through more complex routes, i.e. direct tool-to-tool, floor-to-floor, and building-to-building deliveries.
5. To reduce the AMHS capital and operating costs.

To perform timely wafer deliveries under these circumstances, the AMHS needs to be efficient, flexible, and cost-effective. These challenges seem to become more critical in the next wafer fab generations. It is expected that there will be smaller transfer batches in 300mm Prime, or 450mm wafer fab generations. If, for instance, the size of the transfer batch changes from 25 wafers to 12 wafers, the AMHS will have to process twice as many batches to maintain the same wafer throughput.

Some studies have described the advantages of using conveyors, referred to as continuous flow transporters

(CFT), as the primary AMHS technology within the next fab generation (Pettinato and Pillai 2005). CFTs provide higher transport capacity, shorter and more predictable delivery times, and lower cost-of-ownership than other traditional AMHS methods (i.e. vehicle based AMHS). Conveyors also provide local buffering of material at the processing tool level. The CFT solution for local buffering reduces the need for large stockers or larger process tool footprints.

To minimize cycle time in the next fab generations, Pettinato and Pillai (2005) anticipate models of the CFT-AMHS will have to be integrated with the equipment's scheduling and dispatching tools. Traditionally, discrete-event simulation has been used for modeling the AMHS, but these models are computationally slow. The purpose of this paper is to present an analytical model of an CFT that enables rapid decision making.

This paper is organized as follows. Section 2 describes the problem in more detail. Section 3 presents a review summarizing past published literature relevant to our problem. Section 4 explains our CFT analytical model, and Section 5 provides a comparison between our CFT analytical approach and a simulation approach. Finally, Section 6 states our conclusions and briefly explains our future work.

2 SYSTEM DESCRIPTION

The system modeled in this paper has a typical 300mm AMHS spine layout, illustrated in Figure 1, with a central material handling spine and loops branching on both sides to serve production equipment, located in *bays.* Automated storage units, referred to as stockers, are used to provide both temporary buffering for work-in-process and for transfers between the bays and spine transport systems. In this paper, we will focus our analysis on the CFT *interbay* system because of the heavy traffic due to the reentrant flow in wafer fabs. Wafers will move in groups referred to as lots.

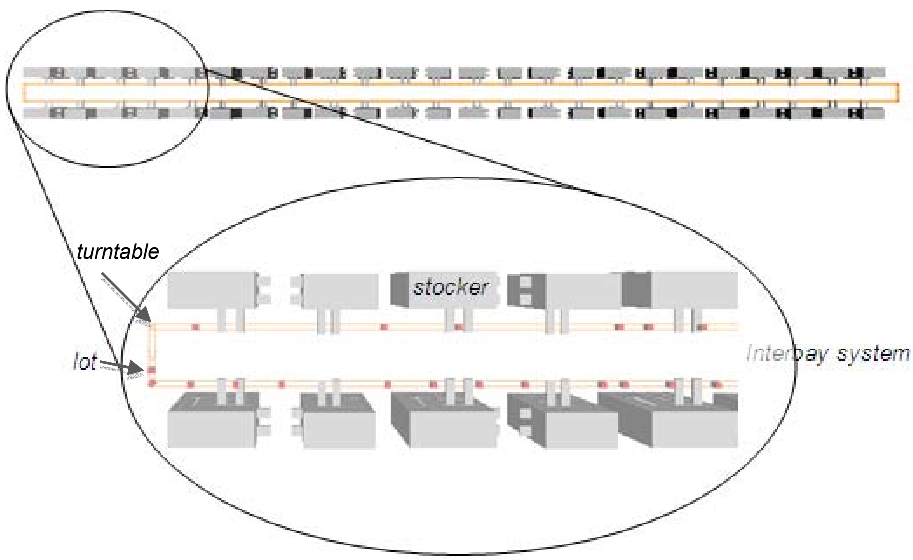

Figure 1: An illustration of an interbay CFT system

It is assumed that the stockers have sufficient capacity so that lots are never blocked. Each stocker is assumed to have both a drop-off station (s_i^d) and a pick-up station (s_i^p). The conveyor systems moves unidirectional, dropping off lots at drop-off stations and picking up lots at pick-up stations.

Lots in the wafer fab will have associated routes which define the sequence of tools (and bays) a lot needs to visit for processing. A lot that completes processing in a particular bay is placed in the associated stocker and waits to be loaded onto the conveyor through the pick-up station. The demand on the intrabay material handling system is a function of both the throughput required for the fab and the routing of the lots.

The conveyor is specified in terms of its speed and length. The length can be described in terms of "windows". A window is defined to hold at most one lot (given all lots are assume to be the same size, all windows are of equal size). The conveyor cycle time is the time required for the conveyor to move the length of one window. The conveyor is assumed to be constantly rotating. Further, lots are assumed to depart from bay *i* via a Poisson process with rate λ_i . The stocker which contains a lot waiting to depart places a lot on the conveyor when the first open window arrives in front of the stocker's pick-up station. The time for a lot to be loaded or unloaded from the conveyor to the stocker is assumed to be constant and less than the conveyor cycle time. Therefore it is assumed the conveyor continues to move while lots are being loaded and unloaded from the stockers.

Turntables are used to make the 90 degree turns in the four corners of the spine intrabay material handling system. These turntables require a constant time for a single lot to enter, rotate the lot 90 degrees, and the lot departs to the next segment of the conveyor. If lots arrive to the turntables at a faster rate than the turntable can rotate and release the lots a queue can develop in front of the turntable. It is assumed that all four turntables operate at the same speed, thus it is not possible for the downstream turntable to block the upstream turntable at either end of the interbay spine.

3 LITERATURE REVIEW

Several publications are concerned with analytical models for closed-loop conveyors with multiple stations, similar to the ones described in Section 2.

Most existing analytical models are designed for a "general" manufacturing environment; their modeling assumptions do not properly characterize conveyors commonly found at wafer fabs. For example, the models presented in Mayer (1960) and Morris (1962) assume that after a load is processed on a station, if it is not able to join the conveyor on its first attempt, it will be permanently set aside. Schmidt and Jackman (2000), on the other hand, assumes that there is no temporary storage of loads after each station. Bastani (1988), Bastani (1990), and Pourbabai and Sonderman (1985) assume that the conveyor has a single loading and multiple unloading stations.

The model presented in this study is an extension of Bozer and Hsieh (2005). Their model assumes that loads are unloaded to (and loaded from) a queue with sufficient capacity so that loads are never blocked. In wafer fabs, stockers typically have amply capacity. Bozer and Hseih also assume that loads arrive to each station according to a Poisson process with a known rate. The Poisson assumption is made by most of the aforementioned studies and is considered reasonable for wafer fabs. It can be justified by the high utilization of processing tools and the re-entrant flow to all the bays, which elevates the departure process variability (Hopp and Spearman 2000), and as a result variability is increased making the assumption of a Poisson distribution for move requests more acceptable. Bozer and Hsieh (2005) also divide the conveyor in equal size windows, each containing at most one load. Like in wafer fabs, they assume the conveyor has a constant speed and length. Lastly, they assume that the load transfer time at loading and unloading stations is constant and less than the time required for the conveyor to move by one window.

One key difference between the model in Bozer and Hseih (2005) and conveyors at wafer fabs is that the latter uses turntables to perform 90° turns in the closed-loop conveyor. Turntables are significantly different from the stations considered in Bozer and Hseih for four reasons: (1) every lot needs to visit a turntable in order to continue in the conveyor; (2) queues before turntables do not have sufficient capacity, which could result in a load being blocked at a loading station; (3) queues after turntables do not have sufficient capacity, which could block the turntable; (4) the service time at the turntable does not follow an Exponential distribution. While many aspects of the turntables are similar to the stations described in Bozer and Hseih these four issues summarize the fundamental differences. In this study we incorporate turntables to the model in Bozer and Hseih (2005).

To the best of our knowledge, there are no analytical models for the interbay conveyor at a wafer fab. Instead, the conveyor-based continuous flow transport (CFT) literature has concentrated on simulation models, for example Arzt and Bulcke (2000), Horn and Podgorski (1998), Paprotny et al. (2000), and Tausch and Hennessey (2002), to mention a few. For a literature review on conveyors models at wafer fabs, as well as a discussion of advantages and disadvantages of using conveyors in wafer fabs, the reader is referred to Nazzal and El-Nashar (2007).

4 ANALYTICAL MODEL

Our objective is to estimate the expected work-in-process (WIP) on the conveyor for a given set of input parameters expressed by the move requirements, the conveyor speed, the layout of the stations on the AMHS closed loop track, the turntables delays, and the window size for each lot.

We propose a two-phase approach to estimating the WIP on the conveyor. In the first phase, we utilize the model that was developed by Bozer and Hsieh (2005) to estimate the expected WIP on the conveyor segment ignoring the queuing delays caused by the turntables. In the second phase, we model two pairs of consecutive turntables (the two shorter side of the spine loop) to estimate the queuing delays caused by these turntables and the accumulated WIP.

4.1 Notation

M: set of stockers in the system.
S: set of loading and unloading stations in the system.
m_i : stocker i, $s_i \in S$.
λ_{ij} : mean arrival rate of move requests from m_i to m_j .

λ_i : mean arrival rate of move requests from m_i .

Λ_i : mean arrival rate of loads to m_i .

S: set of conveyor segments.

s_i : conveyor segment *i* , $s_i \in S$.

w_i : number of windows on segment *i*.

V : conveyor speed (number of windows moved per unit time).

α_i : mean arrival rate of loads to segment *i*.

q_i : probability that segment *i* is occupied, provided that the conveyor system is stable.

WIP_{conv} : the expected work-in-process on the conveyor.

Without loss of generality, we assume that the conveyor loop starts at stocker 1 (m_1), and the sequence of the stockers as encountered by a travelling load on a conveyor is assumed to be m_1 , m_2 ,.., m_i , m_{i+1} ,…, $m_{|M|}$, m_1 , ... Each m_i is assumed to have two stations (load ports): the drop-off station , and the pick-up station . Each station can accommodate one vehicle at a time. Thus, a loop serving |*M*| stockers consists of |*S*|=2|*M*| stations. Loads encounter the drop-off station before the pick-up station for the same stocker.

4.2 Phase I - No turntables

We utilize the model developed in Bozer and Hsieh (2005) that models a closed loop conveyor travelling at a constant speed. As in our system, they assume that the move requests follow a Poisson process and that the loading or unloading times are smaller than the time for a conveyor window to pass a loading/unloading station, and therefore, no queuing of the loads is possible at loading and loading stations.

Bozer and Hsieh (2005), estimate the expected WIP on the conveyor using the expression $WIP_I = \sum_i w_i q_i$. Where $q_i = \alpha_i / V$, α_i is the mean arrival rate of loads to segment *i*, s_i . The α_i values can be obtained by observing that the loads passing through s_i are those that originate from stockers upstream of s_i (stockers *i*-1, *i*-2, …, *i*+1) for delivery to those downstream of and including s_i (stockers *i*, *i*+1, *i*+2, …, *i*-2), where stocker |M+1| is stocker 1.

$$\alpha_i = \sum_{k=i+1}^{i-1} \sum_{l=i}^{k-1} \lambda_{kl}$$

The formula excludes any loads that will not pass through stocker *i*; loads originating from stockers downstream of *i* to stockers upstream of *i*.

Phase *I* analysis provides an estimate for the expected WIP on the conveyor assuming no turntable delays.

4.3 Phase II - Turntables Analysis

In the second phase, we analyze the pair of turntables located at either end of the spine conveyor system. The upstream turntable processes loads placed on the conveyor by the work stations along a particular side of the AMHS loop. The downstream turntable process loads from the upstream turntable as shown in Figure 2. The entire intrabay AMHS can be characterized by two models shown in Figure 2. The first includes the top and left-hand side of the AMHS and the second includes the bottom and right-hand side of the AMHS.

Since the service times for the turntables are identical and deterministic, the downstream table tt_2 will never have any lots waiting in queue, because of the synchronization of the two servers. We therefore only need to analyze the queuing system for tt_1. Assuming that the loads arrive to tt_1 according to a Poisson process, and the turning time is deterministic, we propose to analyze tt_1 as an M/D/1/b system, where b is the number of windows between tt_1 and the upstream station. We can use this analysis for two purposes: (1) estimate the expected WIP waiting for tt_1 (WIP_1), expected queue delays (QT_1), and (2) the expected rate at which loads at the upstream loading station, namely station s_i^p are getting blocked from getting loaded on the conveyor (β_2). This second measure will determine the stability condition for the conveyor; if the effective loading rate, denoted by λ_i^{eff} at s_i^p is less than the rate of move requests by s_i^p , denoted by λ_i , then the conveyor is unable to handle the move requests imposed by the production system it supports.

We now have two stability conditions for the conveyor:

1. The condition derived by Bozer and Hsieh (2005), which states that the conveyor system is stable if and only if the utilization of each segment is less than 100%; $\max_i (q_i) < 1$.
2. The condition stated above: the conveyors system is stable if and only if $\lambda_i^{eff} = \lambda_i$, for $\forall i \in M$.

4.3.1 The M/D/1/b Queuing System

As was mentioned above, the upstream turntables will be modeled as M/D/1/b queuing systems. Buzacott and Shanthikumar (1993) provide a thorough discussion of analyzing general blocking queues, and we will use the following approximation for our analyses, which is also discussed by Hopp and Spearman (2000). We will need additional notation for this part of the analysis, and we will drop the subscripts since the analysis is identical for the two upstream turntables on each side of the aisle:

tt_i : turntable i.
t : delay at a turntable (identical and deterministic).
α : mean arrival rate of loads to the turntable.
u : utilization of the turntable, assuming no blocking.
WIP :expected work-in-process assuming no blocking
ρ : corrected utilization of the turntable due to blocking.
α^{eff} : effective mean arrival rate of loads to the turntable due to blocking.

$$u = \alpha t$$

$$WIP = \left(\frac{1}{2}\right)\left(\frac{u^2}{1-u}\right) + u \qquad (1)$$

$$\rho = \frac{WIP - u}{WIP}$$

$$\alpha^{eff} \approx \frac{1-u\rho^{b-1}}{1-u^2\rho^{b-1}}\alpha$$

We now check for the conveyor stability:

- If $\alpha^{eff} < \alpha$, the conveyor system is unable to handle the move requests because the effective throughput of the conveyor is less than the required throughput to handle all the move requests.
- If $\alpha^{eff} = \alpha$, the conveyor system is able to handle the move requests, and we can use expression (1) to estimate the WIP at each turntable.

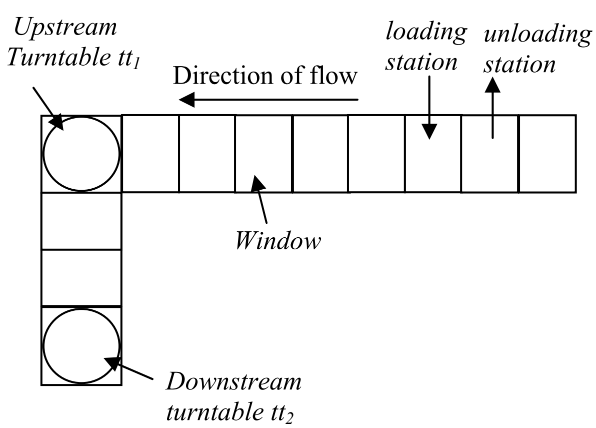

Figure 2: Turntables at each of the interbay CFT

4.3.2 Expected WIP at the Downstream Turntables

We argued above that the tt_2 will not have any lots waiting in queue because of the deterministic and synchronized turning times for all turntables. Therefore, the expected WIP at tt_2 is simply its utilization: $u = \alpha t$.

4.4 Combined WIP

We now combine the expected WIP on the conveyor from phase I analysis in Section 4.2, and the estimated WIP due to the delays at the turntables in Sections 4.3.

$$WIP_{conv} = \underbrace{\sum_{i \in S} w_i q_i}_{\text{Phase I: travelling WIP}} + \underbrace{\left(\frac{u^2}{1-u}\right) + 2u}_{\text{two upstream tunrtables}} + \underbrace{2u}_{\text{two downstream turntables}}$$

5 NUMERICAL EXAMPLE

To evaluate the accuracy of the analytical model, we use a fab simulation model developed and published by International SEMATECH (2001). The SEMATECH virtual fab has 24 bays connected through the interbay system, and each bay has an intrabay material handling system connecting the tools within that bay. We will only use the interbay system to validate the analytical model because of the heavy traffic on the interbay conveyor. The system is illustrated in Figure 1.

The product family modeled in the simulation is SEMATECH's 300mm aluminum process flow for 180nm technology with six metal layers, and 21 masks. For this single product family, ten products are continuously released into the facility. The wafers travel in lots of 25, and the release rate is 20,000 wafers/month (*wpm*) (800 lots/month).

5.1 Experiments

This numerical study is concerned with evaluating the analytical model at a wide range of operating scenarios. We decided to keep the processing time distributions, the process routings and the physical location of the equipment, unchanged and we investigated the impact of the factors listed in Table 1 at different levels.

Table 1: Levels of Factors in the Numerical Analysis

Factor	Levels
Average release rate of lots (λ)	9,000, 18,000, 27,000, and 36,000 *wafers per month (wpm)*
Window size (w)	1, and 1.5 x load width
Turntable turning time (t)	5, 7, 9, 11, and 13 sec
Conveyor speed (V)	1 and 2 ft/sec

There are 96 unique combinations of the selected factors. The simulation model runs until it reaches steady-state before collecting the performance statistics. For each combination of the factors, the simulation is executed with five replications, each runs for 100 days. For each combination, we check for conveyor stability and then we collect the expected WIP on conveyor.

5.2 Comparison Results

Each reported simulation result is the average of five replications. The ratio of the half width of the 90% confidence interval to the mean for all experiments range between 1.2-2.0%.

Tables 2, and 3 illustrate the relative error when comparing the analytical model with the simulation model estimates for the WIP on the conveyor. Within the range that was used in our experiments, the window size has insignificant impact on the relative error in estimating the expected $\boldsymbol{WIP_{conv}}$ and therefore, we show the results for one setting of that factor.

Table 2: Analytical and Simulated Expected WIP on Conveyor (*V = 1 ft/sec, w = 1*)

Release Rate (wpm)	***Turning Time (sec)***	$\boldsymbol{WIP_{conv}}$		
		simulation	***analytical***	***rel. error***
9*K*	5	19.29	19.23	0.3%
18*K*	5	38.74	38.50	0.6%
27*K*	5	58.13	57.83	0.5%
36*K*	5	77.81	77.25	0.7%
9*K*	7	19.60	19.40	1.0%
18*K*	7	39.21	38.87	0.9%
27*K*	7	58.98	58.48	0.8%
36*K*	7	79.21	78.40	1.0%
9*K*	9	19.89	19.56	1.6%
18*K*	9	39.96	39.27	1.7%
27*K*	9	59.88	59.30	1.0%
36*K*	9	81.46	80.41	1.3%
9*K*	11	20.14	19.74	2.0%
18*K*	11	40.37	39.72	1.6%
27*K*	11	61.43	60.46	1.6%
36*K*	11	88.41	87.49	1.0%
9*K*	13	20.30	19.92	1.9%
18*K*	13	41.06	40.24	2.0%
27*K*	13	63.45	62.51	1.5%
36*K*	13	*unstable*	*unstable*	N/A

Based on this case study, the analytical model performs very well with acceptable error percentages. It is able to detect instability caused by an overloaded conveyor or overloaded turntables. On the contrary, the simulation model failed to report the instability in the AMHS system within the run time. We could only detect the instability by examining the growing queues at the loading stations. The analytical model indicated the AMHS inability to handle the high release rates immediately. In terms of execution times, the analytical model gives the results instantaneously, while each simulation run takes around 15-30 minutes per scenario.

Table 3: Analytical and Simulated Expected WIP on Conveyor (*V = 2 ft/sec, w = 1*)

Release Rate (wpm)	***Turning Time (sec)***	$\boldsymbol{WIP_{conv}}$		
		simulation	***analytical***	***rel. error***
9*K*	5	9.95	9.81	1.4%
18*K*	5	19.91	19.65	1.3%
27*K*	5	30.02	29.53	1.6%
36*K*	5	40.16	39.49	1.7%
9*K*	7	10.22	9.97	2.4%
18*K*	7	20.42	20.01	2.0%
27*K*	7	30.82	30.16	2.1%
36*K*	7	41.35	40.54	2.0%
9*K*	9	10.39	10.14	2.4%
18*K*	9	21.03	20.40	3.0%
27*K*	9	31.90	30.93	3.1%
36*K*	9	43.39	42.22	2.7%
9*K*	11	10.67	10.31	3.4%
18*K*	11	21.62	20.84	3.6%
27*K*	11	33.05	31.97	3.3%
36*K*	11	47.93	46.76	2.4%
9*K*	13	10.91	10.49	3.9%
18*K*	13	22.15	21.33	3.7%
27*K*	13	35.01	33.70	3.8%
36*K*	13	*unstable*	*unstable*	N/A

6 FUTURE WORK

We are currently working with AMHS suppliers to calibrate and understand the important issues related to modeling and design of conveyors to support wafer fabs. We will modify the analytical model accordingly to make it more realistic.

We will also explore the possibility of modeling a tool-to-tool conveyor analytically, rather than just for the interbay system as was presented in this paper. In a tool-to-

tool CFT system, the turntables are more prominent because of their presence at each intersection point. We expect that more complex queuing networks are needed to analyze such configurations.

REFERENCES

Arzt, T., and F. Bulcke. 2000. A new low cost approach in 200 mm and 300 mm AMHS. *Semiconductor FABTECH*, 19-26.

Bastani, A. S. 1988. Analytical solution of closed-loop conveyor systems with discrete and deterministic material flow. *European Journal of Operational Research*. 35:187-192.

Bastani, A. S. 1990. Closed-loop conveyor systems with breakdown and repair of unloading stations. *IIE Transactions* 22:351-360.

Bozer, Y. A., and Y-J. Hsieh. 2005. Throughput performance analysis and machine layout for discrete-space closed-loop conveyors. *IIE Transactions* 37:77-89.

Buzacott, J. A., and J. G. Shanthikumar. 1993. *Stochastic models of manufacturing systems*. 1st ed. New Jersey: Prentice-Hall, Inc.

Horn, G. W., and W. A. Podgorski. 1998. A focus on cycle time-vs.-tool utilization “paradox” with material handling methodology. *IEEE SEMI Advanced Semiconductor Manufacturing Conference*.

Hopp W., and M. Spearman. 2000. *Factory physics*. 2nd ed. New York: McGraw-Hill, Inc.

Mayer, H. 1960. Introduction to conveyor theory. *Western Electric Engine.* 4(1):43-47.

Morris, W. T. 1962. *Analysis for materials handling management*. Homewood, Illinois: Irwin.

Nazzal, D., and A. El-Nashar. 2007. Survey of research in modeling conveyor-based automated material handling systems in wafer fabs. In *Proceedings of the 2007 Winter Simulation Conference*.

Paprotny, I., J-Y. Shiau, Y. Huh, and G. Mackulak. 2000. Simulation based comparison of semiconductor AMHS alternatives: continuous flow vs. overhead mono*rail.* In *Proceedings of 2000 Winter Simulation Conference*.

Pettinato, J.S., and D. Pillai. 2005. Technology decisions to minimize 450-mm wafer size transition risk. *IEEE Transactions on Semiconductor Manufacturing* 18(4):501-509.

Pourbabai, B., and D. Sonderman. 1985. A stochastic recirculation system with random access. *Mathematical Modeling* 7:185-196.

Schmidt, L. C., and J. Jackman. 2000. Modeling recirculating conveyors with blocking. *European Journal of Operational Research* 124:422-436.

SEMATECH report. 2001. Q2 2001 productivity analysis factory & cost simulation experiment report. available online at International SEMATECH website <http://www.sematech.org>.

Tausch, F., and L. Hennessey. 2002. Evaluation and comparison of a car-based vs. a CFT material handling system for a 300mm fab. In *Proceedings of the Modeling and Analysis of Semiconductor Manufacturing Conference.*

AUTHOR BIOGRAPHIES

DIMA NAZZAL is an Assistant Professor at the department of Industrial Engineering and Management Systems at the University of Central Florida, Orlando, Florida. She obtained her Ph.D. degree from The H. Milton Stewart School of Industrial and Systems Engineering at Georgia Tech, Atlanta, Georgia, in 2006, and her M.S. in Industrial Engineering from The University of Central Florida. She earned her B.S. in Industrial Engineering from The University of Jordan. She is a member of INFORMS and IIE. Her research interests are in analytical modeling of manufacturing and logistics systems. She can be contacted by email at <dnazzal@mail.ucf.edu>.

ANDREW L JOHNSON is an Assistant Professor in the Department of Industrial and Systems Engineering at Texas A&M University. He obtained his M.S. and Ph.D. in The H. Milton Stewart School of Industrial and Systems Engineering from Georgia Tech, and his B.S. in Industrial and Systems Engineering from Virginia Tech. His research interests include productivity and efficiency measurement, microeconomics, warehouse design and operations, material handling and Internet based database applications. He is a member of the Institute of Industrial Engineers, INFORMS, National Eagle Scout Association, and German Club of Virginia Tech. His email address is <ajohnson@tamu.edu>.

HECTOR J. CARLO is an Assistant Professor of Industrial Engineering at the University of Puerto Rico - Mayagüez. He graduated with a BS in Industrial Engineering from the University of Puerto Rico - Mayagüez (2001), and a MSE (2003) and PhD (2007) from The University of Michigan in Industrial and Operations Engineering. His current research interests include the design and optimization of automated material handling systems, cross-docks, container terminals, and warehouses, as well as Reconfigurable Manufacturing Systems. He is a registered Professional Engineer in the commonwealth of Puerto Rico. His email address is <hcarlo@uprm.edu>.

JESUS A. JIMENEZ is an Assistant Professor in the Industrial Engineering program of the Ingram School of Engineering at Texas State University -San Marcos. He obtained his Ph.D. in Industrial Engineering from Arizona State University, and his M.S. and B.S. in Industrial Engi-

neering from The University of Texas at El Paso. His research interests are in the modeling and analysis of manufacturing systems, especially semiconductor manufacturing; automated material handling systems; the development of manufacturing applications of operations research, computer simulation, and statistics; and the reduction of time required to build, experiment, and analyze complex computer simulation models. His email address is <jesus.jimenez@txstate.edu>.