Simulation Analysis of the Connecting Transport AMHS in a Wafer Fab

James T. Lin, Fu-Kwun Wang, and Chun-Kuan Wu

***Abstract*—This paper analyzes the performance of the connecting transport automated material handling system (AMHS) in a wafer fab. Discrete-event simulation models are developed in *e*-M Plant to study connecting transport in a simplified 300 mm wafer fab. A two-phase experimental approach evaluates the connecting transport. In phase I, the simulation results show that the connecting transport method has a significant effect on average travel time, throughput, and vehicle utilization. The relationship between vehicle quantity and the material flow rate is investigated in a simulation model for three connecting transport methods. The performance measures of these two factors can be predicted with a response surface method. However, none of the connecting transport methods outperforms the others in the different operating scenarios. In phase II, the connecting transport method is a mixture of the three existing methods. Thus, the optimum combination of these methods can be obtained with a mixture of experiment.**

***Index Terms*—Automated material handling system, connecting transport, mixture experiments, simulation analysis.**

I. INTRODUCTION

WITH the current downturn in the semiconductor industry, companies are increasingly shifting capital expenditure away from 200-mm fabs toward 300-mm programs. The major reasons are the availability of more chips per wafer and the more acceptable economies of scale for 300 mm fabs. However, the weight of the 300 mm wafer carriers [which are front-opening unified pods (FOUPs)] exceeds the recommended limit that workers can repetitively move. Thus, 300-mm factories require a much higher level of automation. Such automation results in higher factory efficiency if it is used cost-effectively to ensure that the right material is delivered to the right place at the right time, and that it is processed correctly. For example, some companies' 300-mm strategies include fully automated in-bay material handling. Full-fab automation includes two key elements: an automated material handling system (AMHS) that moves WIP from one process equipment to another, and factory management software that converts the flow of data into information, thus transforming the fab into an intelligent manufacturing environment [1]. An AMHS in semiconductor manufacturing optimizes productivity, improves equipment utilization and ergonomics, and reduces particle contamination and vibration shock to the wafers [2]. Furthermore, fewer operators are necessary. Nevertheless, the savings from modest staff reductions can be offset by the cost of equipment and systems, but automation can generate positive effects on overall equipment effectiveness (OEE), yields, development time, ramp time, and cycle time. These benefits should be substantially greater than those that are accrued from staff reductions [1].

Research into AMHS is generally conducted with simulation analysis, and is directed at track layout, performance analysis, and management issues such as dispatch rules for vehicle control and transport types. Pierce and Stafford [3] studied three types of interbay layout by simulation: spine, perimeter, and custom track systems. The simulation results showed that the custom layout had a 16% more efficient delivery time than the spine layout, and that the perimeter layout had the worst performance in terms of delivery time, vehicle utilization, and track length requirement. The most practical approach to enhancing interbay AMHS performance is to minimize the distances between stockers by using a custom track layout with turntables. Kurosaki *et al.* [4] and Pillai *et al.* [5] addressed the linking of interbay and intrabay track options for a 300-mm fab layout. They found that the delivery time of isolated and linking track systems was highly dependent on the traffic type. Peters and Yang [6] presented a combination of a space filling curve and network flow procedures that could efficiently and effectively solve the integrated layout and material handling system design problem for both the spine and perimeter configurations. Ting and Tanchoco [7] used an analytical approach to develop optimal single-spine and double-spine overhead track layouts and minimize travel distance. They also indicated that the simplicity, track length, and flow distances of the spine layout made it suitable for 300-mm fab.

When the layout and material handling equipment have been determined, performance analysis can be used to evaluate AMHS design alternatives. Cardarelli and Pelagagge [8] used discrete event simulation to examine system performance with such factors 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 AMHS performance. Mackulak *et al.* [9] investigated the relationship between the vehicle carrying capacity and the tool batch size of an intrabay system. The results showed that vehicle capacity had the most significant effect on average delivery time. Paprotny *et al.* [10] compared continuous flow transport (CFT) and overhead monorail vehicles (OMVs). They found that the delivery time of OMV's was half that of the cost-effective CFT system, but the standard deviation of OMV was almost 10 times larger than that of the CFT system. Mackulak and Savory [11] compared the intrabay

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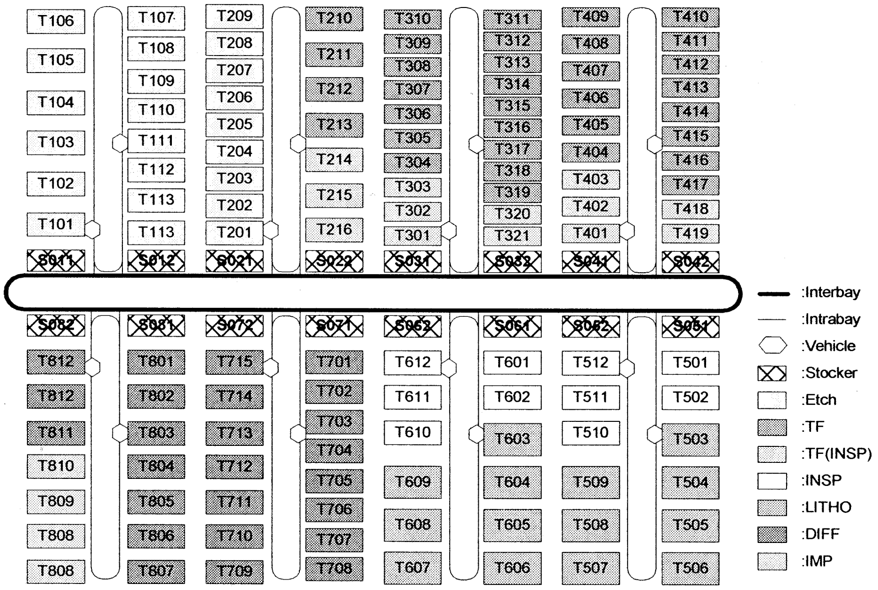

Fig. 1. Representative layout of a 300-mm wafer fab.

layout of two automated material handling systems. The results showed that the average delivery time that was produced by the distributed system was always less than the value that was produced by the centralized system.

AMHS management, such as cost evaluation and vehicle control, has emerged as a new research area. Murray *et al.* [12] performed a financial evaluation of manual and AMHS systems. Through sensitivity analyzes of interest rates, wafer start rates per month, price per die, and yield percentages they showed that the net present value (NPV) of AMHS was favorable to that of the manual handling system. Bahri and Gaskins [13] introduced a logistic algorithm to balance the flow of traffic to and from the load/unload nodes of an interbay delivery system. A simulation model of this algorithm demonstrated up to 30% improvement in lot delivery times. Automatic guided vehicle (AGV) dispatching is widely addressed in the literature on the AMHS of job shop manufacturing. Lin *et al.* [14] employed AGV dispatch rules to evaluate the system performance of a double loop interbay system. They indicated that the dispatch rules had significant effects on delivery time. The simulation results suggested that a combination of the shortest distance (SD) with the nearest vehicle (NV) and first-encounter-first-serve (FEFS) outperformed the other rules. However, most studies only examined the interbay system or the intrabay system. To improve the performance of AMHS in a 300 mm wafer fab, Lin *et al.* [15] proposed the connecting transport concept, using a different type of vehicle between bays than within bays and a single system of interconnected lines. In this paper, the relative performance of the connecting transport AMHS is investigated with *e*-M Plant simulation [16]. The description of a simplified 300-mm AMHS system and its connecting transport are presented in Sections II. The simulation models and experiments, followed by a discussion of the simulation results, are presented in Sections III and IV. Section V presents the analysis of the connecting transport method. Conclusions are made in Sections VI, along with suggestions for further research.

TABLE I
SOME EXAMPLES OF THE LOTS MOVEMENT INFORMATION

Lot	Part	Pieces	Start	Finish	Stngrp	Stnfam	Stn	Due
AK01-A	AK01-A_5	25	02/25/01 23:07:44	02/25/01 23:10:21	DIFF	Exxx	Exxx-01	03/21/01
AK01-A	AK01-A_5	25	02/25/01 23:45:47	02/26/01 00:03:19	TF	Sxxx	Sxxx-06	03/21/01
AK01-A	AK01-A_5	25	02/26/01 00:36:56	02/26/01 01:01:24	LITHO	Ixxx	Ixxx-03	03/21/01

II. SYSTEM DESCRIPTIONS AND THE CONNECTING TRANSPORT OF AMHS

Fig. 1 depicts a representative layout of a 300-mm wafer fab that contains a single loop of an interbay system, eight intrabay systems, and 16 stockers. The vehicle used is the overhead hoist transporter (OHT), which holds the FOUP by its top flange. In general, the tools in a wafer fab can be categorized into six areas: diffusion, etching, implant, lithography, thin-film, and inspection. For this study, a 300-mm wafer fab in Taiwan, R.O.C., is simplified and represented by a total of 123 tools. The layout in Fig. 1 is categorized into four areas, in which the etching area occupies 1.5 bays, the thin-film area occupies 2.5 bays, the lithography area occupies 2 bays, and the implant area occupies 2 bays.

Some examples of the wafer movement information are shown in Table I, and the from-to distance and arrival rate between any tool and any tool are shown on Table II. The arrival rate of the lots is defined as the quantity per hour and this information can be retrieved from the manufacturing execution system (MES). For instance, the lot that was coded by AK01-A entered the process tool Exxx-01 in the diffusion bay at 23:07:44 on 02/25/01, and finished the processing and left at 23:10:21on the same day. The lot arrived 23:45:47 on 02/25/01 at the next tool, Sxxx –06 in the thin–film bay, and left at 00:03:19 on 02/26/01. Thus, using the data from the MES, we can obtain the arrival rate for analysis.

TABLE II
FROM–TO DISTANCE (LOWER CORNER, METERS) AND ARRIVAL RATE (UPPER CORNER, LOT MOVES/HOURS) BETWEEN TOOLS

From-to	**T101**	**T102**	**T103**	**T104**	**T105**	**T106**	**T107**	**T108**	**T109**	**T110**	...
T101		4 0.24	8 0.24	12 0.24	16 0.91	20 0.76	25 0	29 0	33 0	37 0.02	...
T102	55 0.24		4 0.24	8 0.24	12 0.91	16 0.76	21 0	25 0	29 0	33 0.02	...
T103	51 0.24	55 0.24		4 0.24	8 0.91	12 0.76	17 0	21 0	25 0	29 0.02	...
T104	47 0.24	51 0.24	55 0.24		4 0.91	8 0.76	13 0	17 0	21 0	25 0.02	...
T105	43 0.23	47 0.23	51 0.23	55 0.23		4 0.03	9 0	13 0	17 0	21 0.05	...
T106	39 0.02	43 0.02	47 0.02	51 0.02	55 0.02		5 0.01	9 0.01	13 0.01	17 0	...
T107	34 0	38 0	42 0	46 0	50 0.01	54 0.88		4 0.01	8 0.01	12 0	...
T108	30 0	34 0	38 0	42 0	46 0.01	50 0.88	55 0.01		4 0.01	8 0	...
T109	26 0	30 0	34 0	38 0	42 0.01	46 0.88	51 0.01	55 0.01		4 0	...
T110	22 0.04	26 0.04	30 0.04	34 0.04	38 0.03	42 0	47 0	51 0	55 0		...
T111	18.5 0.04	22.5 0.04	26.5 0.04	30.5 0.04	34.5 0.03	38.5 0	43.5 0	47.5 0	51.5 0	55.5 0.12	...
T112	15 0	19 0	23 0	27 0	31 0.01	35 0	40 0	44 0	48 0	52 0	...
	...	...	...	...	...	...	...	...	...	...	

Lin *et al.* [15] proposed the concept of connecting transport. The connecting transport AMHS enables the use of a different type of vehicle between bays than within bays with a single system with interconnected lines. In this connecting transport system, the time that is spent waiting for an empty vehicle is effectively eliminated, and the WIP level can be reduced. Four different vehicle types can be used to carry out the transport tasks from tool to tool, and their descriptions are given as follows. Type-A moves in an intrabay system and carries the lot from tool to tool or between tools and the stockers within the bay. Type-B moves in an interbay system and carries the lot between the stockers. Type-C moves between an intrabay system and an interbay system and carries the lot from a tool in any bay to a stocker in the destination bay. However, when the transport task is complete, the vehicle must return to the original bay. Type-D moves between an intrabay system and an interbay system and carries the lot from a tool in any bay to a tool in any other bay. However, when the transport task is complete, the vehicle must return to the original bay. Furthermore, three different combinations of vehicles are defined as follows.

Method I is a combination of Type-A and Type-B vehicles that isolates the transport between bays from that within each bay. In this situation, the wafer delivery from a tool in one bay to a tool in another bay is conducted through a double stocker operation. Thus, there are longer waiting times for transport vehicles. In addition, the WIP level in this system can be higher. However, the service region for Type-A vehicles is within the bay, and the waiting time for an available vehicle within the bay is shorter.

Method II is a combination of Type-A and Type-C vehicles that connects the transport between bays with that within each bay. In this situation, the wafer delivery from a tool in one bay to a tool in another bay is conducted through a single stocker operation. Thus, the waiting time for interbay transport vehicles of method II is shorter than that of method I, and the WIP level in this system can be reduced. However, the service region for Type-C vehicles is between and within bays, and the waiting time for an available vehicle within the bay is longer.

Method III is a combination of Type-A and Type-D vehicles that connects the transport from any tool to any tool. In this situation, a stocker is only for temporary storage within the bay, and the wafer delivery from a tool in one bay to a tool in another bay is conducted through a single stocker operation or no stocker operation. Thus, the waiting time for transport vehicles in method III is shorter than those in methods I and II. Furthermore, the WIP level in this system can be reduced significantly. However, the service region for Type-D vehicles is between and within bays, and the waiting time for an available vehicle is longer.

Thus, the AMHS design for a 300-mm wafer fab can be one of the proceeding three methods or any mixture of these methods.

III. SIMULATION MODELS AND EXPERIMENTS

Discrete event simulation models were used to evaluate the performance of the methods I, II, and III. The models were built and executed using *e*-M Plant simulation software. *e*-M Plant is

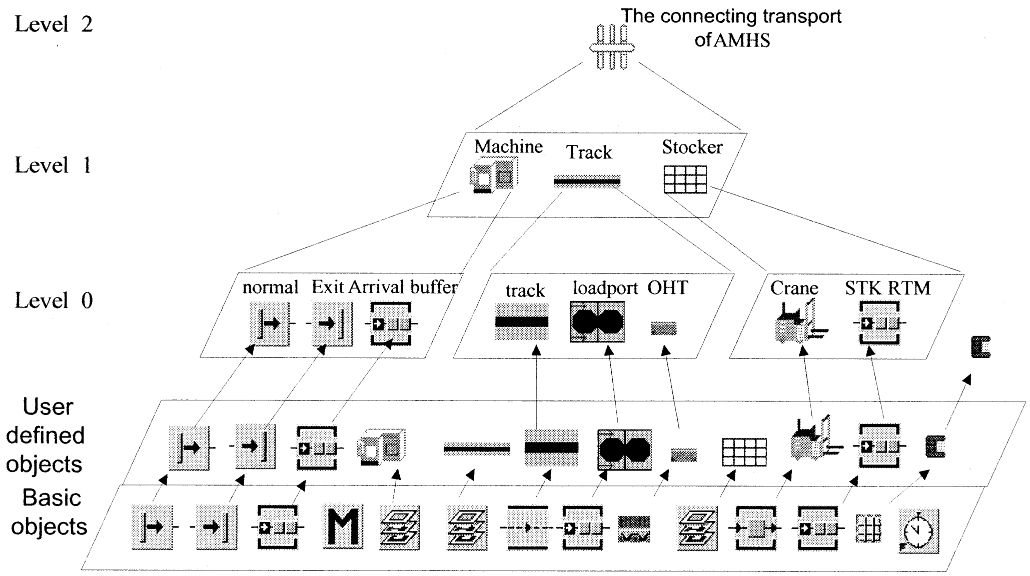

Fig. 2. Hierarchy of a connecting transport AMHS model.

an object-oriented simulation program that has the characteristics of hierarchy, inheritance, and concurrent simulation. Therefore, user-defined objects can be created, such as the OHT vehicle. Several user-defined objects are combined to form a new object, such as a Track consisting of track, loadport, and OHT. The connecting transport AMHS is made up of Machine, Track, and Stocker. Also, the simulation model is developed by the unified modeling language (UML) in which the building procedures can be divided into four phases: inception, analysis, design and implement. Thus, it can save time on model creation. Fig. 2 presents the objects and their relationships in the hierarchy of the simulation model.

This study evaluates the required number of vehicles, throughput, and delivery time. Using these simulation models, which closely match the logic that is implemented for the vehicle control system, ensured the results while minimizing time for model creation, verification, and validation. For each simulation run, several performance measures were collected after 12 h of warm-up time and stored in a data file for the validation. The results provide an approximate estimation of the performance of the proposed facility design. Then, the simulation model was used to analyze different scenarios that were obtained by altering the number of vehicles that were available for product movement. The simulation modeling assumptions are as follows. Vehicles have a constant velocity of 60 m/min. It takes 5 s to move a lot from a stocker or tool to a vehicle. The interarrival times of lots at the source stockers are exponentially distributed. The lots are only transported between process tools, and not processed by the tool, to prevent any differences in process tool performance from affecting the transport vehicle. The number of buffers for each process tool is set at infinity for the same reason. The simulation scope is limited to lot transportation and does not include the scheduling of production.

The three major performance measures that are collected from the simulation are travel time, throughout, and vehicle utilization. Travel time is the time for a lot to travel from the output load port to the input load port of the destination tool. This includes the waiting time between the FOUP issuance of a transportation task at the output load port of the source tool to placement on a vehicle. Throughput is the quantity of FOUPs that complete transport in this system during the simulation time. Vehicle utilization is the percentage of available working time that a vehicle spends moving.

In general, throughput is the most important index in any AMHS system. Hence, throughput has the greatest weight and the other measures are assumed to have lesser, but equal weights. Two factors that might affect the performance of the connecting transport AMHS are flow rate and vehicle quantity. Flow rate can be 290 lots/h, 580 lots/h or 870 lots/h, and number of vehicles can be 0.5 times, 1 times, and 1.5 times. Thus, the factors are tested at 3 by 3 levels, which result in a 3×3 factorial design with 9 experiments. In other words, each combination represents one operational scenario. A number of trial runs were performed to validate the model, and to determine a proper simulation warm-up period. First, it was observed that several statistics in the simulation started to show a smaller variation after about 12 h. Thereafter, there was very little variation among the replications. With this in mind, each simulation in our experiment was run for 228 h after a warm-up period of 12 h. Each experiment was replicated ten times. The total number of simulation experiments performed was 3 (methods) $\times$ 9 (scenarios) $\times$ 10 (replications) $= 270$. Furthermore, the experimental design that was employed was a two-factor, face-centered response surface consisting of 13 experimental trials [17]. The response variables were the average throughput, travel time, and vehicle utilization. Design-Expert software [18] was used to perform the statistical modeling and analysis. Ordinary least squares (OLS) estimation techniques were applied to develop models for each response variable. To fit the best models to the response variables, several selection procedures (stepwise regression, all possible subset regression, C_p, and PRESS) were employed to ensure the best subset models.

TABLE III
SUMMARY OF SIMULATION RESULTS OF MULTIPLE RANGE TEST FOR ALL METHODS

	Average travel time (sec)	Average throughput (lots)	Average vehicle utilization (%)
Scenario 1:	A M-II (1406.6)	A M-III (33652.0)	A M-I (60.1)
flow rate=290 lots/hr	B M-III (3348.2)	A M-I (33007.9)	B M-II (35.8)
# of vehicles = 0.5	C M-I (6164.5)	A M-II (30544.1)	B M-III (35.7)
Scenario 2:	A M-III (189.1)	A M-II (33077.5)	A M-I (51.5)
flow rate=290 lots/hr	B M-II (217.4)	A M-III (33072.2)	B M-II (25.3)
# of vehicles = 1	C M-I (326.6)	A M-I (32867.7)	B M-III (22.6)
Scenario 3:	A M-III (180.4)	A M-II (33061.3)	A M-I (29.5)
flow rate=290 lots/hr	B M-II (199.9)	A M-I (32557.3)	B M-III (17.9)
# of vehicles = 1.5	C M-I (251.8)	A M-III (32273.4)	B M-II (16.5)
Scenario 4:	A M-II (764.6)	A M-III (47762.1)	A M-I (60.8)
flow rate=580 lots/hr	B M-I (1215.2)	AB M-II (45568.8)	B M-II (36.4)
# of vehicles=0.5	C M-III(1497.2)	B M-I (39981.4)	B M-III (35.8)
Scenario 5:	A M-III (176.7)	A M-I (48980.7)	A M-I (41.4)
flow rate=580 lots/hr	B M-II (198.8)	A M-III (45341.5)	B M-III (20.4)
# of vehicles=1	C M-I (268.4)	A M-II (44225.8)	B M-II (177.2)
Scenario 6:	A M-III (140.6)	A M-II (48022.2)	A M-I (24.3)
flow rate=580 lots/hr	B M-II (182.4)	A M-I (47025.9)	B M-II (13.7)
# of vehicles=1.5	C M-I (242.0)	A M-III (44836.0)	C M-III (8.4)
Scenario 7:	A M-I (299.7)	A M-I (57577.0)	A M-I (50.7)
flow rate=870 lots/hr	B M-III (375.4)	B M-III (48247.5)	B M-III (28.5)
# of vehicles=0.5	C M-II (845.6)	B M-II (46932.3)	B M-II (23.8)
Scenario 8:	A M-III (151.7)	A M-III (55141.4)	A M-I (25.3)
flow rate=870 lots/hr	B M-II (184.7)	A M-II (50516.0)	B M-III (18.7)
# of vehicles=1	C M-I (247.4)	A M-I (49863.9)	C M-II (14.2)
Scenario 9:	A M-III (152.1)	A M-II (57979.2)	A M-I (16.9)
flow rate=870 lots/hr	B M-II (179.7)	AB M-I (50470.3)	B M-II (11.1)
# of vehicles=1.5	C M-I (217.6)	B M-III (47620.1)	B M-III (11.0)

Note: 1) M-I= the combination of type-A and type-B; M-II= the combination of type-A and type-C; M-III= the combination of type-A and type-D; 2) Methods with the same letter of the English alphabet (A, B, C) represent they are not significantly different at 95% confidence level.

IV. ANALYSIS OF SIMULATION RESULTS

For each connecting transport method, the residual analysis showed that the assumptions (normality, constant variance for error term and independent) were satisfied for all scenarios, and further statistical analysis could be carried out. The results of the analysis of variance in Table III indicate that the connecting transport method significantly affects the average travel time at 95% confidence level for all scenarios. The method significantly affects the average throughput for scenarios 4, 7, and 9, and significantly affects the average vehicle utilization for all scenarios at 95% confidence level. The least significant difference (LSD) method is used to compare all pairs of the three connecting transport methods under each of the nine scenarios. Results of the paired test analysis are summarized in Table III. The three methods are ranked best (top) to worst under each scenario for average travel time, average throughput, and vehicle utilization. Each value is the mean of the performance data that was collected in the 10 replications. An overall 95% confidence level is used in paired test analysis. With these methods, three pairwise comparisons can be conducted under each scenario for each performance measure. The information that is contained in Table III can provide guidance for decision makers in the selection of preferable methods, based on the different operation environment and performance measures. Ranking comparisons for all three methods based on Table III show that no method outperformed the others. The generated response models for the different methods are as follows.

Method I:

$$\begin{aligned}\text{Travel time} =& 14\,920.89 - 13.49 \times \text{flowrate} - 17\,156.97\\ &\times \text{vehicle ratio} + 4501.86 \times \text{vehicle ratio}^2\\ &+ 10.05 \times \text{flowrate} \times \text{vehicle ratio}\\ \text{Throughput} =& 8409.10 + 101.37 \times \text{flowrate} - 0.059\\ &\times \text{flowrate}^2\\ \text{VU} =& 90.08 - 0.028 \times \text{flowrate} - 33.60\\ &\times \text{vehicle ratio}.\end{aligned}$$

The R^2 values are 0.8299, 0.8452, and 0.9366, respectively. The residual analysis of these models validated the assumptions. A three-dimensional (3-D) surface for the desirability function is presented in Fig. 3. Flow rate and vehicle number had significant effects on travel time and vehicle utilization. However, throughput was only affected by the flow rate.

Method II:

$$\begin{aligned}\text{Travel time} =& 3351.22 - 1.29 \times \text{flowrate} - 4535.14\\ &\times \text{vehicle ratio} + 1588.08 \times \text{vehicle ratio}^2\\ &+ 0.93 \times \text{flowrate} \times \text{vehicle ratio}\end{aligned}$$

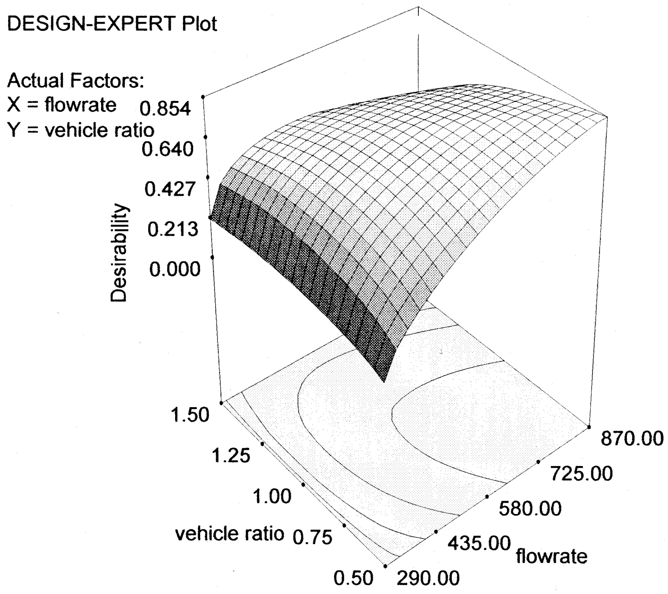

Fig. 3. 3-D surface for the desirability function using the method I.

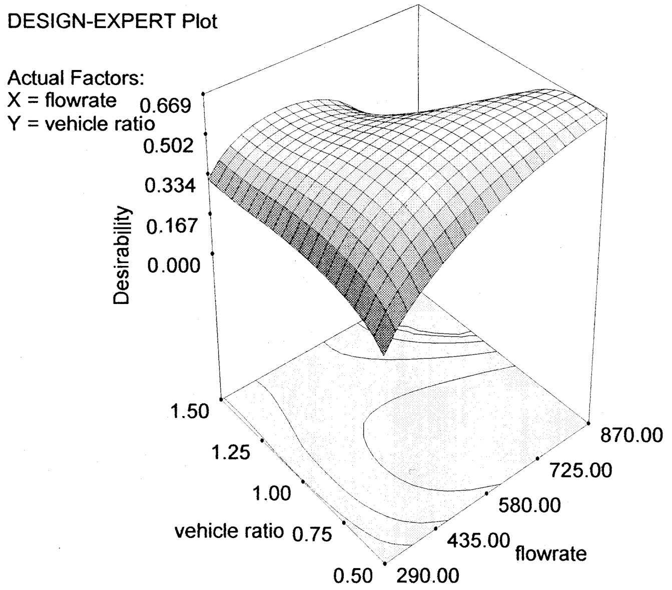

Fig. 4. 3-D surface for the desirability function using the method II.

$$\begin{aligned}\text{Throughput} =& 16\,692.86 + 60.13 \times \text{flowrate} - 3190.53\\ &\times \text{vehicle ratio} - 0.035 \times \text{flowrate}^2\\ &+ 14.71 \times \text{flowrate} \times \text{vehicle ratio}\\ \text{VU} =& 64.51 - 0.016 \times \text{flowrate} - 55.15\\ &\times \text{vehicle ratio} + 18.45 \times \text{vehicle ratio}^2.\end{aligned}$$

The R^2 values are 0.9378, 0.9663, and 0.9346, respectively. The residual analysis of these models validated the assumptions. A 3-D surface for the desirability function is presented in Fig. 4. Flow rate and vehicle number had significant effects on travel time, throughput, and vehicle utilization.

Method III:

$$\begin{aligned}\text{Travel time} =& 8009.25 - 12\,806.63 \times \text{vehicle ratio}\\ &+ 5048.21 \times \text{vehicle ratio}^2\\ \text{Throughput} =& 25\,327.83 + 29.89 \times \text{flowrate}\\ \text{VU} =& 58.52 - 0.010 \times \text{flowrate} - 44.10\\ &\times \text{vehicle ratio} + 11.60\\ &\times \text{vehicle ratio}^2.\end{aligned}$$

The R^2 values are 0.8469, 0.8394, and 0.9365, respectively. The residual analysis of these models validated the assumptions. A 3-D surface for the desirability function is presented in Fig. 5. Flow rate and vehicle number had significant effects on travel time and vehicle utilization. However, throughput was only affected by the flow rate. Furthermore, one can use the generated models to predict the performance measures for any specified flow rate and the ratio of vehicles.

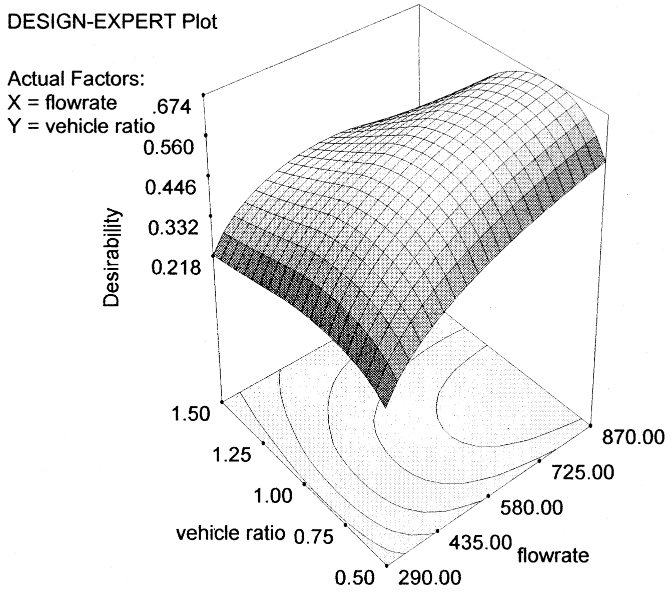

Fig. 5. 3-D surface for the desirability function using the method III.

V. ANALYSIS OF THE CONNECTING TRANSPORT METHOD

A mixture experiment is a special type of response surface experiment in which the factors are the ingredients or components of a mixture, and the response is a function of the proportions of each ingredient [17]. Hence, the transport strategy can be defined as the mixture of three connecting transport methods, and let X_i represent the proportion of the i^{th} method in the mixture. That is, $X_1 + X_2 + X_3 = 1, 0 \leq X_i, i = 1, 2, 3$. Moreover, the experimental analysis uses a simplex lattice design.

Two factors that might affect the performance of the connecting transport AMHS are identified: the flow rate and the transport method. The flow rate can be 290 lots/h, 580 lots/h or 870 lots/h. A new connecting transport method is defined as the mixture of three connecting transport methods, and the design points are set to 13 (see Table IV). Furthermore, the numbers of vehicles for different mixtures of these three methods under different flow rates are shown in Tables V–VII. Here, the simulation assumptions and performance measures are the same as that of the experimental design in Section III. Each experiment was replicated ten times, and the total number of simulation experiments performed was 3 (flow rates) × 13 (strategies) × 10

TABLE IV
MIXTURE EXPERIMENT

Design point	Type-A and Type-B	Type-A and Type-C	Type-A and Type-D
S-1	1.00	0.00	0.00
S-2	0.00	1.00	0.00
S-3	0.00	0.00	1.00
S-4	0.33	0.67	0.00
S-5	0.67	0.33	0.00
S-6	0.33	0.00	0.67
S-7	0.67	0.00	0.33
S-8	0.00	0.33	0.67
S-9	0.00	0.67	0.33
S-10	0.67	0.17	0.17
S-11	0.17	.067	0.17
S-12	0.17	0.17	0.67
S-13	0.33	0.33	0.33

(replications) $= 390$. The generated response models for the different flow rates are given follows.

1) Flow rate $=$ 290 lots/h:

$$\begin{aligned}
\text{Travel time} =& 306.90 \times M - I + 217.05 \times M - II \\
&+ 204.75 \times M - III \\
&- 194.43 \times M - I \times M - II \\
&- 267.89 \times M - I \times M - III \\
&- 162.02 \times M - II \times M - III \\
&- 575.52 \times M - I \times M - II \times M - III \\
\text{Throughput} =& 32\,359.39 \times M - I + 33\,010.59 \times M - II \\
&+ 33\,488.18 \times M - III \\
&+ 2353.77 \times M - I \times M - II \\
&- 874.36 \times M - I \times M - III \\
&- 5625.10 \times M - II \times M - III \\
&+ 8477.77 \times M - I \times M - II \times M - III \\
\text{VU} =& 46.67 \times M - I + 25.74 \times M - II \\
&+ 26.13 \times M - III \\
&- 34.41 \times M - I \times M - II \\
&- 33.79 \times M - I \times M - III \\
&- 25.49 \times M - II \times M - III \\
&- 173.28 \times M - I \times M - II \times M - III
\end{aligned}$$

The R^2 values are 0.8272, 0.4204, and 0.7697, respectively. The residual analysis of these models validated the assumptions. A 3-D surface for the desirability function is presented in Fig. 6. Under these models and a cubical region, the optimal setting is (method-I, method-II, method-III) $=$ (63%, 37%, 0), with travel time $= 228$, throughput $= 33151$, and vehicle utilization $= 31\%$.

2) Flow rate $=$ 580 lots/h:

$$\begin{aligned}
\text{Travel time} =& 262.75 \times M - I + 199.81 \times M - II \\
&+ 169.81 \times M - III \\
&- 126.64 \times M - I \times M - II \\
&- 118.40 \times M - I \times M - III \\
&- 80.54 \times M - II \times M - III \\
&- 705.38 \times M - I \times M - II \times M - III \\
\text{Throughput} =& 48\,848.26 \times M - I + 44\,064.00 \times M - II \\
&+ 45\,351.63 \times M - III \\
&+ 8486.56 \times M - I \times M - II \\
&- 11\,265.01 \times M - I \times M - III \\
&+ 7507.49 \times M - II \times M - III \\
&- 10\,671.87 \times M - I \times M - II \times M - III \\
\text{VU} =& 39.26 \times M - I + 17.93 \times M - II \\
&+ 22.19 \times M - III \\
&- 24.95 \times M - I \times M - II \\
&- 15.47 \times M - I \times M - III \\
&- 2.52 \times M - II \times M - III \\
&- 210.24 \times M - I \times M - II \times M - III
\end{aligned}$$

The R^2 values are 0.9486, 0.4095, and 0.8974, respectively. The residual analysis of these models validated the assumptions. A 3-D surface for the desirability function is presented in Fig. 7. Under these models and a cubical region, the optimal setting is (method-I, method-II, method-III) $=$ (79%, 0, 21%), with travel time $= 222$, throughput $= 46202$, and vehicle utilization $= 33\%$.

3) Flow rate $=$ 870 lots/h:

$$\begin{aligned}
\text{Travel time} =& 244.47 \times M - I + 185.49 \times M - II \\
&+ 153.13 \times M - III \\
&- 80.75 \times M - I \times M - II \\
&- 146.23 \times M - I \times M - III \\
&- 43.32 \times M - II \times M - III \\
&- 105.39 \times M - I \times M - II \times M - III \\
\text{Throughput} =& 50\,164.67 \times M - I + 51\,589.51 \times M - II \\
&+ 54\,124.87 \times M - III \\
&+ 4092.45 \times M - I \times M - II \\
&- 4428.96 \times M - I \times M - III \\
&- 2688.51 \times M - II \times M - III \\
&+ 94\,090.13 \times M - I \times M - II \times M - III \\
\text{VU} =& 25.15 \times M - I + 14.87 \times M - II \\
&+ 18.45 \times M - III \\
&- 5.85 \times M - I \times M - II \\
&- 8.32 \times M - I \times M - III \\
&- 7.30 \times M - II \times M - III \\
&+ 12.73 \times M - I \times M - II \times M - III
\end{aligned}$$

The R^2 values are 0.9889, 0.5328, and 0.9355, respectively. The residual analysis of these models validated the assumptions. A 3-D surface for the desirability function is presented in Fig. 8. Under these models and a cubical region, the optimal setting is (method-I, method-II, method-III) $=$ (40%, 23%, 37%), with travel time $= 160$, throughput $= 54610$, and vehicle utilization $= 18\%$. The confirmatory runs under these conditions at different flow rates showed that all of the responses satisfied the requirements.

VI. CONCLUSION

A performance evaluation of the connecting transport of an automated material handling system (AMHS) in a wafer fab was

TABLE V
NUMBER OF VEHICLES FOR DIFFERENT STRATEGIES UNDER THE FLOW RATE = 290 LOTS/H

	S-1		S-2		S-3		S-4			S-5			S-6			S-7		
Bay	A	B	A	C	A	D	A	B	C	A	B	C	A	B	D	A	B	D
1	1	4	1	2	1	2	1	2	1	1	3	1	1	2	1	1	3	1
2	1		1	2	1	2	1		2	1		1	1		1	1		1
3	1		1	2	1	2	1		2	1		1	1		1	1		1
4	1		1	2	1	2	1		1	1		1	1		1	1		1
5	1		1	2	1	2	1		2	1		1	1		1	1		1
6	1		1	2	1	2	1		1	1		1	1		1	1		1
7	1		1	1	1	1	1		1	1		1	1		1	1		1
8	1		1	1	1	1	1		1	1		1	1		1	1		1

	S-8			S-9			S-10				S-11				S-12				S-13			
Bay	A	C	D	A	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
1	1	1	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	2	1	1
2	1	1	1	1	2	1	1		1	1	1		2	1	1		1	1	1		1	1
3	1	1	1	1	2	1	1		1	1	1		2	1	1		1	1	1		1	1
4	1	1	1	1	1	1	1		1	1	1		1	1	1		1	1	1		1	1
5	1	1	1	1	2	1	1		1	1	1		2	1	1		1	1	1		1	1
6	1	1	1	1	1	1	1		1	1	1		1	1	1		1	1	1		1	1
7	1	1	1	1	1	1	1		1	1	1		1	1	1		1	1	1		1	1
8	1	1	1	1	1	1	1		1	1	1		1	1	1		1	1	1		1	1

Note: A= the vehicle Type-A; B= the vehicle Type-B; C= the vehicle Type-C; D= the vehicle Type-D

TABLE VI
NUMBER OF VEHICLES FOR DIFFERENT STRATEGIES UNDER THE FLOW RATE = 580 LOTS/H

	S-1		S-2		S-3		S-4			S-5			S-6			S-7		
Bay	A	B	A	C	A	D	A	B	C	A	B	C	A	B	D	A	B	D
1	2	7	2	3	1	3	2	3	2	2	5	1	1	3	2	2	5	1
2	2		2	4	1	3	2		3	2		2	1		2	2		1
3	2		2	4	1	3	2		3	2		1	1		2	2		1
4	2		2	3	1	3	2		2	2		1	1		2	2		1
5	2		2	4	1	4	2		3	2		2	1		2	2		1
6	2		2	3	1	3	2		2	2		1	1		2	2		1
7	1		1	1	1	2	1		1	1		1	1		1	1		1
8	1		1	2	1	2	1		1	1		1	1		1	1		1

	S-8			S-9			S-10				S-11				S-12				S-13			
Bay	A	C	D	A	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
1	1	1	2	2	2	1	2	5	1	1	2	2	2	1	1	2	1	2	2	3	1	2
2	1	2	2	2	3	1	2		1	1	2		3	1	1		1	2	2		2	2
3	1	1	2	2	3	1	2		1	1	2		3	1	1		1	2	2		2	2
4	1	1	2	2	2	1	2		1	1	2		2	1	1		1	2	2		1	2
5	1	2	2	2	3	1	2		1	1	2		3	1	1		1	2	2		2	2
6	1	1	2	1	2	1	2		1	1	2		2	1	1		1	2	2		2	2
7	1	1	1	1	1	1	1		1	1	1		1	1	1		1	1	1		1	1
8	1	1	1	1	1	1	1		1	1	1		1	1	1		1	1	1		1	1

Note: A= the vehicle Type-A; B= the vehicle Type-B; C= the vehicle Type-C; D= the vehicle Type-D

conducted by considering the effects of the connecting transport method. Using *e*-M Plant simulation models, the capabilities of this method were demonstrated. The following conclusions can be made.

TABLE VII

THE NUMBER OF VEHICLES FOR DIFFERENT STRATEGIES UNDER THE FLOW RATE = 870 LOTS/H

	S-1		S-2		S-3		S-4			S-5			S-6			S-7		
Bay	A	B	A	C	A	D	A	B	C	A	B	C	A	B	D	A	B	D
1	3	11	3	4	1	4	2	4	3	3	7	2	2	4	3	2	7	2
2	3		3	5	1	5	3		4	3		2	3		4	2		2
3	3		3	5	1	5	3		4	3		2	3		4	3		2
4	3		3	4	1	4	2		3	3		2	2		3	2		2
5	3		3	5	1	5	2		4	3		2	2		4	2		2
6	3		3	5	1	5	2		4	3		2	2		4	2		2
7	1		1	2	1	2	1		1	1		1	1		1	1		1
8	1		1	2	1	2	1		2	1		1	1		2	1		1

	S-8			S-9			S-10				S-11				S-12				S-13			
Bay	A	C	D	A	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
1	2	2	3	2	3	2	3	7	1	1	2	2	3	1	2	2	1	3	2	4	2	2
2	2	2	3	2	4	2	3		1	1	3		4	1	2		1	3	2		2	2
3	2	2	3	2	4	2	3		1	1	3		4	1	2		1	3	3		2	2
4	1	2	3	2	3	2	2		1	1	2		3	1	2		1	3	2		2	2
5	1	2	3	2	4	2	3		1	1	2		4	1	1		1	3	2		2	2
6	1	2	3	2	4	2	2		1	1	2		4	1	1		1	3	2		2	2
7	1	1	1	1	1	1	1		1	1	1		1	1	1		1	1	1		1	1
8	1	1	2	1	2	1	1		1	1	1		2	1	1		1	2	1		1	1

Note: A= the vehicle Type-A; B= the vehicle Type-B; C= the vehicle Type-C; D= the vehicle Type-D

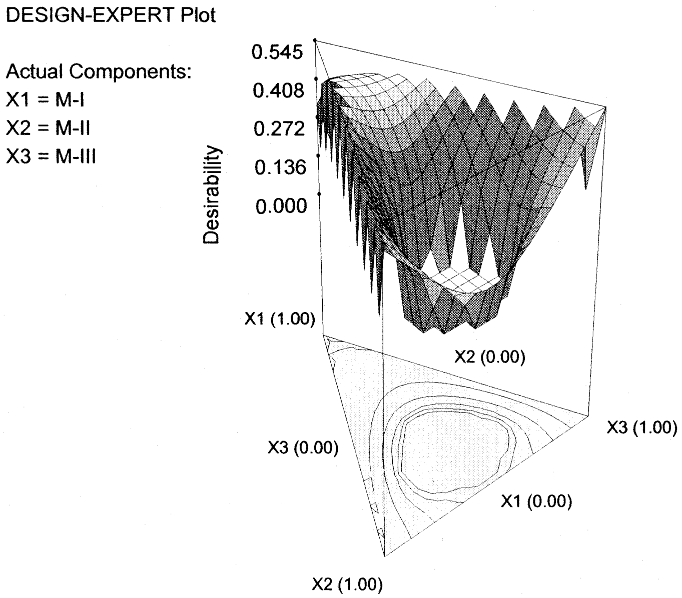

Fig. 6. 3-D surface for the desirability function using the mixture design for flow rate = 290 lots/h.

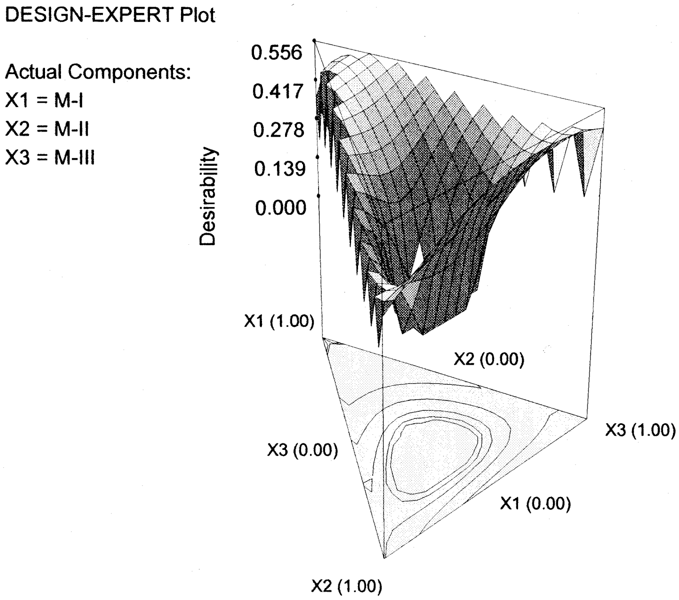

Fig. 7. 3-D surface for the desirability function using the mixture design for flow rate = 580 lots/h.

The results show that the combination of vehicles has a significant effect on average travel time, throughput, and vehicle utilization. When travel time is the major concern, the suitable method is the combination of Type-A and Type-D vehicles. When throughput is the major concern, the suitable method is the combination of Type-A and Type-C vehicles. When vehicle utilization is the major concern, the suitable method is the combination of Type-A and Type-B vehicles. However, no one method outperformed the others in all operational scenarios.

The optimum combination of vehicle numbers and the material flow rate can be obtained with a response surface methodology. The system engineer can then use this model to predict the system performance based on different values of the two factors.

Furthermore, the mixture of the three connecting transport methods can improve the performance measures of average travel time and vehicle utilization. The optimal combination

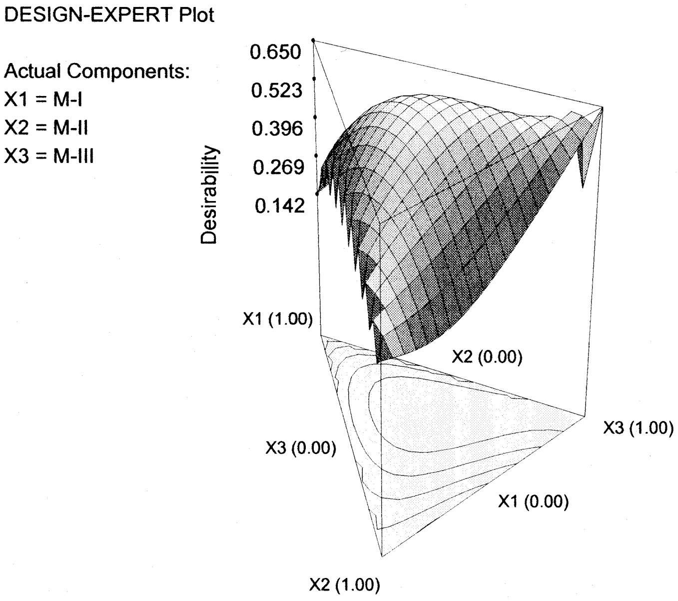

Fig. 8. 3-D surface for the desirability function using the mixture design for flow rate $= 870$ lots/h.

of the connecting transport methods can be obtained with a response surface methodology. The system engineer can then use this model to predict the system performance based on different mixtures of the three methods.

Future research could focus on the integration of the lot transportation and lot scheduling. Moreover, the effect of dispatch rules on the connecting transport merits further study.

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REFERENCES

[1] M. Chase, D. Scott, and J. Nestel-Patt, "The challenge of macro integration for fully automated 300 mm fabs," *Solid State Technol.*, vol. 52, no. 10, pp. 52–64, 2000.

[2] G. Nadoli and D. Pillai, "Simulation in automated material handling systems design for semiconductor manufacturing," in *Proc. Winter Simulation Conf.*, 1994, pp. 892–899.

[3] N. G. Pierce and R. Stafford, "Modeling and simulation of material handling for semiconductor wafer fabrication," in *Proc. Winter Simulation Conf.*, 1994, pp. 900–906.

[4] R. Kurosaki, N. Nagao, H. Komada, Y. Watanabe, and H. Yano, "AMHS for 300 mm wafer," in *IEEE Int. Symp. Semiconductor Manufacturing Conf.*, 1997, pp. D-13–16.

[5] D. Pillai, T. Quinn, K. Kryder, and D. Charlson, "Integration of 300 mm fab layouts and material handling automation," in *Proc. IEEE/CHMT Ninth Int. Electronic Manufacturing Technology Symp.*, 1999, pp. 23–26.

[6] B. A. Peters and T. Yang, "Integrated facility layout and material handling system design in semiconductor fabrication facilities," *IEEE Trans. Semiconduct. Manufact.*, vol. 10, pp. 360–369, Aug. 1997.

[7] J. H. Ting and J. M. A. Tanchoco, "Optimal bi-directional spine layout for overhead material handling systems," *IEEE Trans. Semiconduct. Manufact.*, vol. 14, pp. 57–64, Feb. 2001.

[8] G. Cardarelli and P. M. Pelagagge, "Simulation tool for design and management optimization of automated interbay material handling and storage systems for large wafer fab," *IEEE Trans. Semiconduct. Manufact.*, vol. 8, pp. 44–49, Feb. 1995.

[9] G. T. Mackulak, F. P. Lawrence, and J. Rayter, "Simulation analysis of 300 mm intrabay automation vehicle capacity alternatives," in *Proc. IEEE/SEMI Advanced Semiconductor Manufacturing Conf.*, 1998, pp. 445–450.

[10] I. Paprotny, W. Zhao, and G. T. Mackulak, "Reducing model creation cycle time by automated conversion of a cad amhs layout design," in *Proc. Winter Simulation Conf.*, 1999, pp. 799–783.

[11] G. T. Mackulak and P. Savory, "A simulation-based experiment for comparing amhs performance in a semiconductor fabrication facility," *IEEE Trans. Semiconduct. Manufact.*, vol. 14, pp. 273–280, Aug. 2001.

[12] S. Murray, G. T. Mackulak, J. W. Fowler, and T. Covlin, "A simulation-based cost modeling methodology for evaluation of interbay material handling in a semiconductor wafer fab," in *Proc. Winter Simulation Conf.*, 2000, pp. 1510–1510.

[13] N. Bahri and R. J. Gaskins, "Automated material handling system traffic control by means of node balancing," in *Proc. Winter Simulation Conf.*, 2000, p. 1344.

[14] J. T. Lin, F. K. Wang, and P. Y. Yen, "Simulation analysis of dispatching rules for an automated interbay material handling system in wafer fab," *Int. J. Prod. Res.*, vol. 39, no. 6, pp. 1221–1238, 2001.

[15] J. T. Lin, F. K. Wang, and C. K. Wu, "The connecting transport of automated material handling system in wafer fab," *Int. J. Prod. Res.*, vol. 41, no. 3, pp. 529–544, 2003.

[16] *Objects Manual Version 4.5*, Tecnomatix Technologies GmbH & Co, Stuttgart, KG, 2000.

[17] R. H. Myers and D. C. Montgomery, *Response Surface Methodology* New York, Wiley, 1995.

[18] *Design-Expert, Version 5.0.8*, Minneapolis, MN, 1997.

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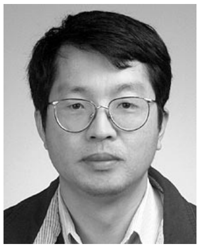

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