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A SIMULATION-BASED COST MODELING METHODOLOGY FOR EVALUATION OF INTERBAY MATERIAL HANDLING IN A SEMICONDUCTOR WAFER FAB

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ABSTRACT

In the next generation of semiconductor wafer fabrication facilities, decisions concerning material handling systems will be a major factor in initial facility cost, operational cost, production cycle times, and possibly product yield percentages. The wafers will increase in diameter to 300 mm and a new front opening unified pod (FOUP) has been designed to carry them, both increasing the weight of a production lot. This increase requires substantial automation for ergonomic and quality reasons. As a result, semiconductor manufacturers are asking, "What level of automation is financially justifiable?"

Automation suppliers have stated that automation saves money, but have as yet not produced a sufficiently detailed financial analysis proving their premise. In this paper, both a fully automated and a manual material handling system are simulated and compared in a thorough cost analysis. Sensitivity analysis is performed on inflation rate, interest rate, die price, wafer start rate, and yield percentage to validate the results of the analyses.

1 INTRODUCTION

Semiconductor manufacturers are in the process of designing their next generation factories (300mm). As these designs begin to firm, it is apparent that they will need to rely heavily on automated material handling systems (AMHS) for WIP movement and storage (Colvin and Mackulak 1999). Automation will be required for ergonomic, yield and quality reasons. The size, value, and content of a front opening unified pod (FOUP) make it unlikely that manual movement approaches are a realistic alternative (Weiss 1999). Most 300mm designs therefore approach the movement and storage issues by specifying interbay and intrabay AMHS equipment as required system components.

However, a semiconductor manufacturer needs to know the financial implications of automation. In fact, many 200mm production facilities would like to know whether it is cost advantageous to retrofit an existing facility or explain the financial benefit of the existing system to their management. Automation suppliers have stated that automation saves money, and over the past ten years or so, many design and optimization models targeting material handling equipment have been built, but they have yet to produce a sufficiently detailed financial analysis proving their premise (Cardarelli and Pelagagge 1995). This paper presents a study that examines the financial issues of automation and evaluates the cost/benefits of implementation to determine whether AMHS equipment truly is financially justifiable.

2 BACKGROUND

This project was funded by PRI Automation, Inc., a leader in the design and manufacture of AMHS for the semiconductor industry. The project began in September 1999 and was completed in December of 1999.

In 1998, a former PhD student at Arizona State University created a semiconductor manufacturing fab model using Factory Explorer®, an integrated capacity, cost, and cycle time analysis software tool for manufacturing (Wright, Williams and Kelly 1995). In the model, the production of 300mm wafers (used in the production of DRAM) was simulated using a process flow of about 450 steps. The model included 398 process tools in 75 tool groups. Process tool downtimes for both preventative and unexpected maintenance were incorporated, along with employee lunches and breaks. The results of the simulations were somewhat theoretical, though, in that only actual machine processing was used when calculating cycle time. No material movement times were included. When the model was run, a cycle time of about 2.3X was observed when capacity loading was set to 85% with a start rate of 20,000 wafers/month.

3 AUGMENTING THE MODEL

To begin searching for the financial advantages of AMHS, the project team set out to find out if the promised savings really existed. The specific objective during the first stage of the project was to determine if one system performed the required interbay moves significantly faster than the other. To answer this question the material movement steps were integrated into the process flow. The integration techniques and assumptions are discussed below.

3.1 Fab Layout Selection

Most wafer fabrication facilities are arranged in a "farm" style layout that has like process tools grouped by area. This could be a bay/chase or ballroom type layout. Therefore, the layout shown in the figure below was selected for use in the project. The layout was provided by PRI and deemed especially suitable for the investigation. The tools here are grouped by tool type, therefore requiring more interbay movements than facilities incorporating other tool grouping methods (Yang 1997).

3.2 Parameters Added Affecting Both Material Handling Systems

The floor plan was used to determine two important particulars: which machines were located in each bay, and the distance separating the bays from one another. These data then needed to be combined with the steps in the DRAM model process flow. Using both, and the assumptions listed below, the total distance traveled during the production of a single wafer was determined.

- A stocker was assumed to be at the front of each bay.
- All interbay movements were assumed to be from stocker-to-stocker.
- All movements occurred along straight paths aligned with the walls of the hallway, and all turns were made at right angles.
- When the next step in the process flow required a type of machine that was located in more than one bay within the fab, and one of the machines was in the current bay, that machine was utilized, eliminating any interbay movement.
- When the next step in the process flow required a type of machine that was located in more than one bay within the fab, and one of the machines was ***not*** in the current bay, the model assumed that the product had to travel to the machine that was the furthest away.

3.3 Manual Material Handling System Integration

For the model to simulate the manual material handling system, a new operator group (manual operators), and a new tool group (stocker load/unload positions), were created. Initial simulations indicated that 35 operators total, and 2 stocker load/unload positions per bay were necessary to avoid creating bottlenecks. Other assumptions, specific to the manual system, are listed below and depicted graphically in Figure 2.

- The move operators were assumed to "appear" immediately in front of the appropriate stocker when an interbay movement request was made.

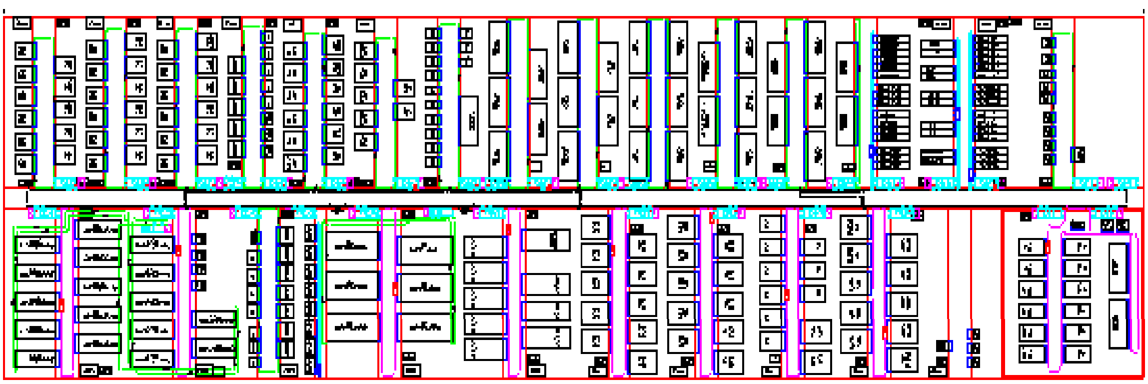


Figure 1: The Bay and Chase Facility Used in Calculations

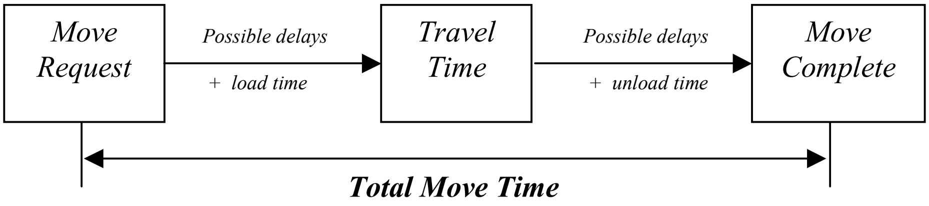


Figure 2: Schematic Representation of a Manual Movement

- Each bay was equipped with exactly two stocker load/unload positions for storage and transport purposes. Gaining access to the stockers was therefore resource contingent. The resulting delays were calculated in the model.
- The times required to load and unload the product were 1 minute each.
- The average traveling speed for each operator/PGV was assumed to be 2 miles/hr; a reasonable walking speed when considering the weight of the PGV.
- To compensate for safety precautions and other human factors in the fab, travel times used were equal to [distance/speed]*α, where α is equal to 1.5.
- All manual traveling times were exponentially distributed.

3.4 AMHS Integration

To attain plausible data for automated movement times, advanced simulation tools were needed. Employees at PRI generated a realistic AMHS model of this layout, and completed several simulations using the distances found in this particular fab. From these simulation runs, PRI put together a set of move times associated with the AMHS which incorporated all load, unload, and resource contingency delays.

These average values had a variety of distributions that best fit the times associated with each movement. However, considering the system as a whole, the log normal distribution was adequately representative. Unfortunately, Factory Explorer is not equipped to handle a log normal distribution, and a new interpretation was required.

After some further investigation, a shifted exponential distribution was settled on. However, its use required some adjustment in the numbers to represent the actual data as closely as possible. Generally, the shifted exponential distribution uses the minimum possible value and the mean of the data to create the shape of the distribution. Because the actual minimum value of the time data had a very low probability of occurring, it wouldn't have been practical to use the minimum value. Therefore, the number used was the adjusted minimum, which was calculated to be sum of the actual minimum plus half of the difference between the mean and the actual minimum.

Incorporating an adjusted minimum simply eliminated the opportunity for the software model to choose values that were the extremely unlikely times for each move.

4 SIMULATION RESULTS

Because the original model was designed with a maximum capacity of 20,000 wafers/month, a simulation run of the modified model with an initial start rate of 16,000 wafers/month (and an add rate of 1000 wafers/month) was performed. It ran once with the manual material handling data incorporated, and once with the AMHS information. Six replicates were completed, making the range of start rates in the simulation 16-21K.

In order to determine if there was indeed some significant advantage of one system over the other, a solid basis for comparison needed to be constructed. This basis was built around the '3X statistic'. In the industry, one of the most informative statistics of any wafer fab is the ratio of average cycle time to the raw processing time. A ratio equal to three is commonly referred to as '3X' and is used as an optimistic but realistic goal for the actual operation of a fab (Fowler *et al.*1997). Visually, the 3X statistic can be seen on the characteristic curve of a system. Two systems can be compared easily using their curves as shown in the example in Figure 3. This figure demonstrates that as the start rate increases, the ratio of cycle time to raw process time increases as well. The system with the higher start rate at 3X is more desirable.

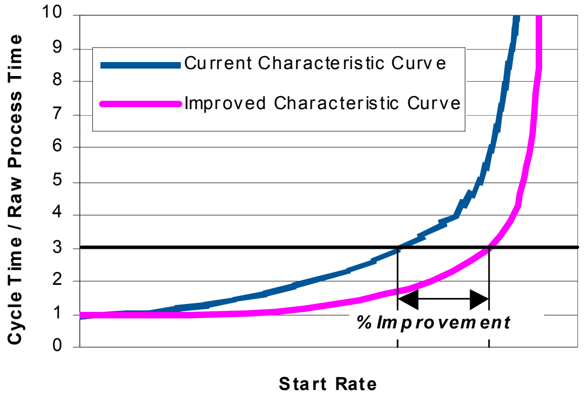


Figure 3: A Sample Characteristic Curve Analyzed at 3X

Table 1: Simulation Data with Start Rates Ranging from 16-21K

Start Rate	Handling System	Average Cycle Time (Days)	Raw Process Time (Days)	*3X RPT (Days)*	Cycle Time Over RPT	% of Max Capacity
16000	**AMHS**	29.1	16.3	*48.9*	1.78	79.6
	Manual	29.2	16.8	*50.4*	1.73	79.6
17000	**AMHS**	31.4	16.3	*48.9*	1.92	84.6
	Manual	32.1	16.8	*50.4*	1.90	84.6
18000	**AMHS**	35.3	16.3	*48.9*	2.16	89.5
	Manual	35.7	16.8	*50.4*	2.12	89.5
19000	**AMHS**	41.8	16.3	*48.9*	2.56	94.5
	Manual	42.1	16.8	*50.4*	2.50	94.5
20000	**AMHS**	63.2	16.3	*48.9*	3.88	99.5
	Manual	65.2	16.8	*50.4*	3.87	99.5
21000	**AMHS**	98.0	16.3	*48.9*	6.01	104.5
	Manual	101.4	16.8	*50.4*	6.02	104.5

The simulation results from the manual and AHHS indicated that the two systems' performances were surprisingly similar. Looking at the respective characteristic curves the two systems are difficult to discern from one another, so the parameters for comparison are listed in Table 1 rather than graphically.

Based on the assumptions made in section 3.3, the raw process time per wafer is slightly lower in the automated system, and though they are very close, the AMHS average cycle times are consistently lower than the manual times. In addition, as the throughput increased, the margin between the two increased. This implied that the higher the production volume, the greater the benefit of the automated system, however further investigation was required to verify this conclusion.

For the models in this investigation, a **3X RPT** column in Table 1 is given and this represents the realistic number of days required to fabricate one product from start to finish.

The table illustrates that the start rate that corresponds to the 3X statistic falls in between 19 and 20K for both handling systems. In order to narrow the gap and determine the exact value of the start rate at 3X, simulations were run using start rates ranging from 19 to 20K at intervals of 200 wafers/month. The resulting data is shown in Table 2.

These curves demonstrate that the values in question occur between the 19.4 and 19.6K start rates, thus narrowing the gap even further. From here, it was possible to interpolate between the values and find a very close approximation of the start rate for each system at 3X; however, the approximations can still be improved.

Because the product model is dependent on random values from a variety of distributions, the values calculated at the end of a single simulation run are really only one of numerous possible results. Multiple simulations at each start rate were conducted to achieve a higher level of confidence in the estimations of average cycle time.

Doing so also provided a means for the calculation of the standard deviation of each of the cycle times, also listed in Table 2. These standard deviations reveal that the manual model has less variability than the AMHS when the start rates are low. However, when the start rates increased, the

Table 2: Simulation Data with Start Rates Ranging from 19.4-19.6K with Interpolated Start Rates for 49-Day Cycle Times

Material Handling	Start Rate	Average Cycle Time (Days)	Avg. Cycle Time St. Dev	Raw Process Time (Days)	*3X RPT (Days)*	Cycle Time Over RPT	% of Max Capacity
Manual	19400	48.0	0.60	16.8	*50.4*	2.85	96.5
	19448	***49.0***					
	19600	52.2	1.2	16.8	*50.4*	3.10	97.5
AHMS	19400	47.7	0.78	16.3	*48.9*	2.93	96.5
	19459	***49.0***					
	19600	52.1	1.1	16.3	*48.9*	3.19	97.5

manual system's variability was higher than that of the AMHS. The differences in the variability's are small, but their behaviors follow the logical assumption that as workload increases, machines perform more consistently than humans. This, again, validated the factory model.

Because 3X was different for the manual and automated material handling systems, a slightly altered basis for comparison was required. Any number of days close to the 3X approximations would have been suitable, and for this analysis, 49 days was selected. It is very near both numbers, it's an integer, and it falls almost exactly in the middle of the two actual values.

As seen in Table 2, the average cycle times for the AMHS are still slightly, but consistently, lower than those in the manual system. Thus, the fab running the interbay AMHS can start slightly more wafers per month while achieving the 49 day average cycle time.

To approximate the 3X values of wafer starts/month more accurately, linear interpolation was applied. The results are also listed in Table 2 and suggest that the fab running AMHS can produce ≈11 more wafers per month.

5 COST EVALUATION

To complete the cost evaluation, several discrete variables needed to be chosen. PRI supplied many of these values directly, and approved those selected by the project team. Table 3 contains the critical model parameters and their selected values.

These values, along with the results of the simulation, were plugged into the cost model for further analysis as the 'base case'. In the model, the data were transformed using several formulae and an extensive calculation procedure.

6 COST MODEL RESULTS AND SENSITIVITY ANALYSIS

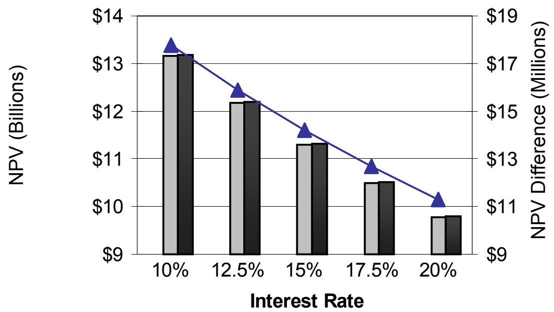
Initial calculations showed that the net present value of the AMHS was $14.22 million greater than that of the manual system. In order to determine the stability of the model output in various real world circumstances, sensitivity analysis was performed on several of the variables. One of the goals of the sensitivity analysis was to ascertain a combination of parameters that showed equal net present values for the two systems. The team was interested in determining if there was a limit to when the AMHS system was more advantageous. Each parameter and the results of the analysis are discussed here.

6.1 Interest and Inflation Rates

Figure 4 illustrates the NPV of the base case over a range of interest rates (located across the x-axis). The inflation rate here is 5%. The net present values, plotted against the axis on the left, are in *billions* of dollars, the exact difference in *millions*, is plotted against the axis on the right. The figure indicates that as the interest rate increased, the net present value of both systems decreased, and the margin separating the two systems decreased as well. Therefore, the higher the interest rate, the less advantage the AMHS demonstrated over the manual system. It was not until the interest rate reached 42.3% however, that the difference disappeared completely.

Table 3: Parameter and Values Used in the Model

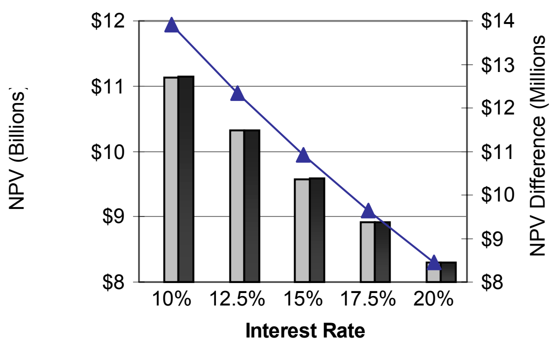
Parameter	Manual	AMHS
Periods per Year	1	1
Starting and Ending Years	1998-2003	1998-2003
Number of Products	1 (DRAM)	1 (DRAM)
Operator levels	2	1
Salaries (operators)	$25/hr	$25/hr
Operator Cost	$14,016,000	$4,204,800
Total Tool Costs	$2,109,228,000	$2,109,228,000
Building Cost	$300,000,000	$300,000,000
Material Handling Equipment Cost	$11,675,000	$22,095,000
Information System	$100,000,000	$100,000,000
Utilities	$100,000,000	$100,000,000
Interest Rate	15%	15%
Inflation Rate	5%	5%
Wafer Starts-Out-WIP / month	19448	19459
Selling Price	$100	$100
Yield	95%	95%
Operators (4 Shifts)	60 Technicians –140 Operators	60 Technicians
Hours per year	8,760	8,760



	10%	12.5%	15%	17.5%	20%
Manual, $B	$13.15	$12.18	$11.30	$10.50	$9.780
AMHS, $B	$13.17	$12.19	$11.31	$10.51	$9.791
NPV Diff, $M	$17.76	$15.90	$14.22	$12.70	$11.31

Figure 4: NPV Comparison with 49-Day Cycle Time

The next parameter to be tested was the inflation rate. Figure 4 represented the base case with an inflation rate of 5%. To see if this parameter had a large effect on the NPV, the same analysis was completed using 0% inflation rate. These results are displayed in Figure 5.



	10%	12.5%	15%	17.5%	20%
Manual, $B	$11.13	$10.31	$9.577	$8.906	$8.297
AMHS, $B	$11.14	$10.32	$9.588	$8.916	$8.305
NPV Diff, $M	$13.91	$12.34	$10.92	$9.63	$8.46

Figure 5: NPV Comparison with 49-Day Cycle Time and 0% Inflation Rate

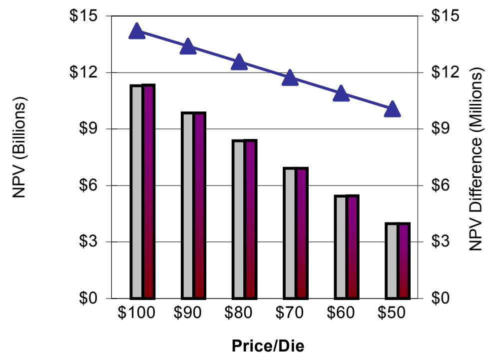
The reduction in the inflation rate lowered the NPV across the board, and the same trend in the difference in the two NPVs appeared. This time, the difference disappeared when the interest rate rose to approximately 35.5%.

From this analysis, it was determined that the model reacts to changes in interest rates and inflation rates, however, their effects did not alter the initial conclusions. The AMHS still apeared to be the better investment at the most realistic interest and inflation rates.

6.2 Die Prices

In the model base case, each die was assumed to sell at a price of $100. Due to the fluxuation of this number in reality, it was necessary to find out how sensitive the NPVs were to price reductions.

Sensitivity analysis was performed on this parameter next. The price was decreased all the way down to $50/die at $10 increments. The resulting NPVs are plotted in Figure 6. Here, it can be seen as the price per die decreased, the net present value of both systems decreased, and the margin separating the two systems decreased as well. Therefore, it seems that the higher the price per die, the more advantage the AMHS has over the manual system.



	$100	$90	$80	$70	$60	$50
Manual, $B	$11.3	$9.83	$8.36	$6.89	$5.43	$3.96
AMHS, $B	$11.3	$9.84	$8.38	$6.91	$5.44	$3.97
NPV Diff, $M	$14.2	$13.3	$12.5	$11.7	$10.9	$10.0

Figure 6: NPV Comparison with 49-Day Cycle Time at Various Price per Die

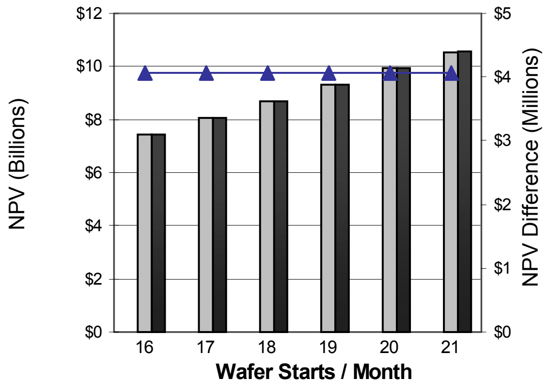
6.3 Start Rate and Yield Percentage

Next, a few parameters *within the factory* were examined. The base case scenario described above used the start rates determined to be at a common estimate of 49 days average cycle time, 19,448 wafers/month for manual and 19,459 for AMHS. For this analysis, start rates ranging from 16,000 to 21,000 were input to the cost model for both systems.

As can be seen in Figure 7, when the start rates increased, the NPVs of both systems increased at approximately the same rate. Therefore, regardless of the start rate, the AMHS is the better investment once again. Additional comparisons were made at 19.4 and 19.6K for each system, but the results provided no new information.

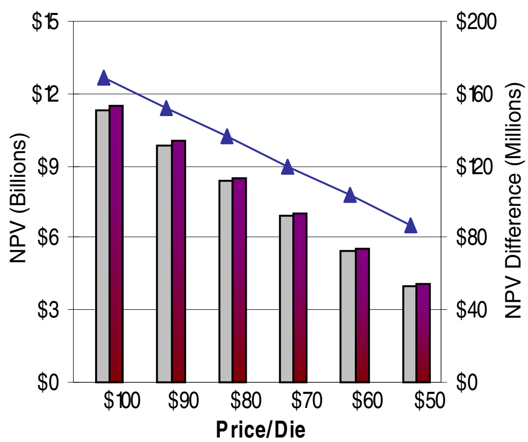
The second factory parameter evaluated was yield percentage. It can be argued that factories running an AMHS likely produce less defective product than those with manual material handling systems increasing yield by up to one percent. This sensitivity analysis assumed this to be valid and determined the resulting increase in the NPV.

Yield percentage in the base case for both systems was 95%, and here it was varied between 95% and 96% for the AMHS. From Figure 8, it can be seen that the NPV increased as the yield increased, returning the highest values at the highest price per die, as expected.



	16	17	18	19	20	21
Manual, $B	$7.426	$8.050	$8.674	$9.298	$9.922	$10.54
AMHS, $B	$7.430	$8.054	$8.678	$9.302	$9.926	$10.55
NPV Diff, $M	$4.058	$4.058	$4.058	$4.058	$4.058	$4.058

Figure 7: NPV Comparison with 49-Day Cycle Time with Various Start Rates



	$100	$90	$80	$70	$60	$50
MAN (95%), $B	$11.303	$9.835	$8.367	$6.899	$5.432	$3.964
AMHS (96%), $B	$11.471	$9.987	$8.503	$7.019	$5.535	$4.051
NPV Diff, $M	$168.81	$152.52	$136.23	$119.94	$103.65	$87.37

Figure 8: NPV Comparison with 49-Day Cycle Time with Various Prices per Die and Yield Percentages

Operating under the previous assumption, when the manual system with a 95% yield was compared to the AMHS with 96% yield and with a die price of $100, the potential increase in net present value after five years would be a substantial *$170 million.*

7 CONCLUSIONS

After comparing the two material handling systems for 300mm wafer fabs through the sensitivity analysis of the effective rate, wafer start rate per month, price per die, and yield percentage, the net present value evaluation clearly favors the AMHS as the best investment.

An evaluation of the NPV cash flows indicated that the AMHS system became more profitable than the manual alternative during the fourth year of operation in the base case. At the end of the five-year period, the net present value for the AMHS system was higher than that of the manual system for all of the scenarios considered.

8 FUTURE WORK

Several scenarios could be investigated to validate and expand upon these results. Other sensitivity analyses could be performed in order to determine if variations in assumed values have a large effect on the results. The parameters in question in the simulation calculations are that of walking speed, the multiplying factor, the number of stocker load/unload positions in each bay for manual material handling, and the adjusted minimum value used in the shifted exponential distribution of the AMHS data.

A second investigation could attempt to apply the model and methodology to a very different facility layout or to the production of a different product. The 300mm fabs of the future are expected to alter the class-one clean room requirements throughout the fab allowing for a wide variety of floor plans to be utilized. Dramatically different facilities could be compared to evaluate their respective benefits.

Finally, and perhaps the most interesting, would be an analysis of intrabay material handling systems. In industry, it has been predicted that advances in intrabay material handling technology will cut substantial amounts from the yearly operational budget. The methodology of this project could be applied to an intrabay handling situation in an attempt to substantiate these predictions.

REFERENCES

Cardarelli, G. and P.M. Pelagagge, 1995. Simulation tool for designed and management optimization of automated interbay material handling and storage systems for large wafer fab. *IEEE Transactions on Semiconductor Manufacturing* 8 (1): 44-49.

Colvin, Theron and Gerald Mackulak, 1999. Fab design and development methodology much change to allow for successful integration of all systems. *Semiconductor Fabtech* 10: 155-166.

Fowler, J.W., Brown, S.W., Gold, H., Schoemig, A., "Measurable Improvements in Cycle-Time Constrained Capacity", *Proceedings of the Sixth International Symposium on Semiconductor Manufacturing*, San Francisco, CA, pp. A21-A24, 1997.

Weiss, Mitchell, 1999. New twists on fab design and layout. *Semiconductor International* (July): 103-108.

Wright, Williams and Kelley, 1995. *User Manual, Factory Explorer Version 2.7*. Pleasanton, CA: Wright Williams and Kelly.

Yang, Taho and Brett A. Peters, 1997. A spine layo9ut design method for semiconductor fabrication facilities containing automated material-handling systems. *International Journal of Operations & Production Management* 17 (5): 490-501.

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