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Control wafers inventory management in the wafer fabrication photolithography area

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An important variable affecting the production throughput in the wafer fabrication photolithography area is the work-in-process (WIP) level of control wafers. Previous research work has focused on control wafers downgrading problem, and little work has been done for WIP level of control wafers. The objective of this paper is to develop methods for estimating the WIP level of control wafers for each grade, while maintaining the same level of production throughput. Two factors are considered, the re-entrant of control wafers within the same grade and the downgrading of control wafers among different grades. Under pulling control production environment, a multi-loop algorithm is developed for estimating the WIP control wafers for each grade. We conduct some simulation experiments based on a real-world factory production environment to demonstrate the effectiveness of the proposed algorithm. The results show that the algorithm is an efficient tool for estimating the cycle time and WIP level for each grade of control wafers.

Keywords: Photolithography area; Control wafers; Inventory; Multi-loop; Re-entrant; Downgrade

1. Introduction

In the wafer fabrication photolithography area, control wafers are utilized for monitoring and measuring the particle content, measuring photo-resist coat thickness and uniformity, examining focus and de-focus, checking critical dimension, and inspecting overlaps (Lin 2000). The purpose of using control wafers is to assure that manufacturing process in a wafer fabrication can satisfy the required specifications. Control wafers are repeatedly used until their quality and thickness no longer conform to the process requirement. For control wafers that do not conform to the process requirements, they are either downgraded or discarded. To avoid pollution to factory machines due to the misuse of control wafers, managers often apply grade concepts of control wafers for diverse machine types according to the requests of processing circumstances,

such as the degree of quality. Any shortage of control wafers may result in a halt of machine operations and as a consequence, may seriously affect the process yield and production planning. To avoid such situations occurring, a large number of control wafers are usually prepared and stored for use. This, however, unnecessarily increases the WIP level of control wafers. For most factories, the work in process (WIP) level of control wafers is 30–50% of that for normal products, with 30% being the benchmark as indicated by Lin (2000).

Existing methods for estimating cycle time include the simulation approach, statistical regression approach, analytical method, and hybrid method. The pros and cons of these existing methods have been examined by several researchers (Lawrence 1995, Glynn and O'Dea 1997, Raddon and Grigsby 1997). Discrete event simulations are used to create shop floor condition and are a useful tool for performance prediction. The use of statistical regression approach with variance analysis explores the relationship between cycle time and system variables to construct a cycle time forecasting

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model. Wang *et al.* (1997) combined Little's formula (Hiller 1995) with Kingman's equation (Kleinrock 1975) to develop a regression function for estimating cycle time at each work station. Analytical method uses the queuing systems theory as a base to develop formulas for flow time estimation according to the distribution hypothesis on parameter setting. The hybrid method combines various methods to provide the cycle time estimation. Chung *et al.* (1999) studied analytical methods incorporating simulation techniques to develop a cycle time estimation method.

Spearman and Woodruff (1990) evaluated the Kanban's CONWIP system and pointed out that CONWIP is a suitable pull system in many dynamic environments. Popovich *et al.* (1997) designed a re-use matrix that takes into account the contamination level of the used test wafers as well as other characteristics of wafers. This is useful in determining possible usage for the used wafers. Although the re-use process requires manual operation, it provides a less expensive alternative to buying new wafers. Kroese and Nicola (1999) suggested a two-node tandem Jackson (1963) network model with simulation for general arrival and service system to estimate the ratio of overflow in the second buffer. Chen and Lee (2000) studied the effect of control/dummy (C/D) wafers downgrading based on push or pull systems. They concluded that the pull system is preferred if machine delay time is the primary concern, whereas the push system leads to a better utilization of C/D wafers and a lower C/D wafers level. Kumar and Kumar (2001) introduced the queuing network models to analyse system performance of semiconductor wafer fabrications. They surveyed some sequencing rules and release policies used in semiconductor manufacturing.

Although these studies have provided some important information regarding the cycle time and WIP level estimation, there has been little research done on control wafers inventory management. The purpose of this paper is to present an algorithm for estimating the control wafers cycle time and the WIP level for each control wafer grade. Under the production control environment with a pulling system, a multi-loop control wafers (MCW) algorithm is developed, and the re-entrant and downgrade manufacturing factors to set the WIP level of control wafers for each grade are considered. This investigation provides a useful reference to the management level for setting the WIP level for each grade and to increase inventory management performance. The remainder of this paper is organized as follows. Section 2 describes the control wafers management problem and assumptions. Section 3 presents the construction of control wafers multi-loop management system and describes the MCW algorithm.

In section 4, some simulation experiments are conducted, and the simulation results are presented to show the effectiveness of the proposed algorithm. In section 5, some conclusion remarks are made.

2. Problem description and assumptions

Control wafers are employed for monitoring machine parameters in the production process and for maintaining manufacturing conditions of semiconductor wafer fabrication. Control wafers are used not only to control the machine manufacturing capability, but also to increase the process yield. An increase in control wafers WIP level would result in an increase in the holding cost but with a decrease in the shortage cost; therefore, a trade-off decision must be made. Most common decisions in current industrial practice often result in maintaining each grade of control wafers at its maximum service level. This paper attempts to determine appropriate WIP level of control wafers for each grade in the system. How to determine the optimal WIP level of control wafers for each grade is important to the performance of the inventory management system. This paper considers a control wafers management problem where control wafers can be re-used in the same grade, downgraded for use in a different grade or discarded in the last grade. In order to simplify the complexity of the environment, we shall restrict our investigation of control wafers to the photolithography area in a wafer fabrication.

In general, the re-use status of control wafers can be divided into (1) pre-disposition, (2) in-use, and (3) recycle, termed the PUR process (Chen and Lee 2000). The in-use control wafers in the photolithography area provide functions for product monitoring, equipment monitoring, breakdown and recovery monitoring, and preventive maintenance (Lin 2000). In this paper, multi-loop system concept is applied to the establishment of the downgrade and PUR process.

A diagram of multi-loop control wafers system is depicted in figure 1. In figure 1, node *Start* contains new control wafers, node *Finish* is the discard wafers collection, and a_{01} is the new wafers depletion rate to loop 1. Each loop can be considered as a neuron, and the j th loop can be considered as the j th grade of control wafers process. The depletion rate of j th grade control wafers is d_j , re-entrant ratio is P_{ij} (for $i=j$), downgrade ratio is P_{ij} (for $i < j$), discard ratio is P_{ij} (for $j=D$), and arrival rate is λ_j . Figure 2 displays the relationship between PUR and downgrade in the j th loop system of control wafers. In figure 2, the loop consists of three stages, and each stage consists of one

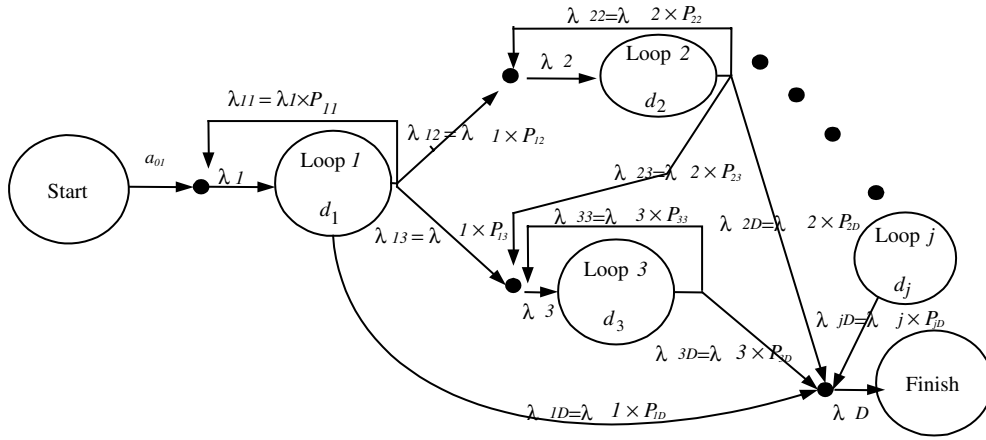


Figure 1. The multiple loop control wafers system.

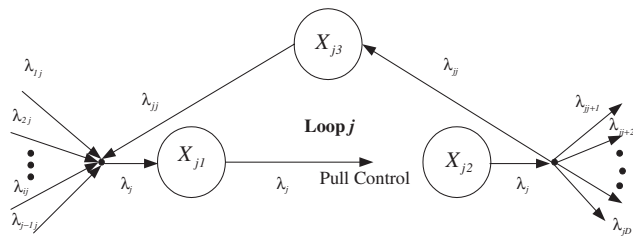


Figure 2. The relationship of downgrade, pull control and PUR process in the *j*th loop system.

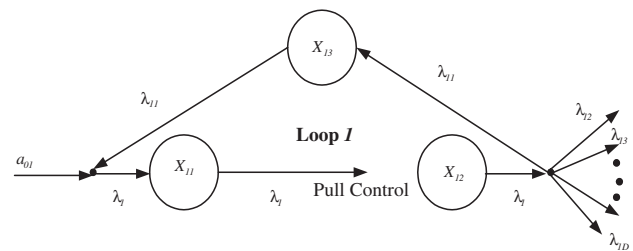


Figure 3. The relationship of new control wafers, pull control and PUR process in the 1st loop system.

machine for processing. X_{j1} represents the pre-disposition stage, X_{j2} represents the in-use stage, and X_{j3} represents the recycling stage. At the pre-disposition stage, operations must be completed to make sure that the control wafers comply with the manufacturing condition before they can be used. At the in-use stage, control wafers are employed in wafer fabrication to monitor and control some machine functions. After control wafers passing through the pre-disposition and in-use stages, they either enter the re-entrant state, or are downgraded or discarded. For the *j*th grade of control wafers, re-entrant arrival rate is λ_{ij} (for $i=j$), downgrade arrival rate is λ_{ij} (for $i < j$), discard rate is λ_{jD} , and arrival rate is λ_j . If the control wafers enter the re-entrant state, they will be repeatedly used and remain in the PUR process. Figure 3 is a specific case for the loop system shown in figure 2. It displays the relationship between PUR and new arrival rate in the 1st loop system of control wafers, where the new arrival rate of control wafers is a_{01} .

The MCW algorithm developed here is based on the following assumptions:

- Daily demand rate for each grade is given. It is related to the schedule for normal product fabrication.

- Demand rate equals supply rate. In a pull system, when a control wafer is required in a grade, it will be pulled from the upper grade. With no shortage permitted, demand rate (d_j) should equal to supply rate (λ_j). The interval time between two pulls is set to $1/d_j$ ($1/\lambda_j$) for loop 2 and loop 3.
- The process time in each machine is given. The process of C/D wafers in a machine normally includes tasks such as the measurement of particle content, and the process time is usually a constant or normally distributed.
- Each PUR process consists of three stages of operation, and each stage has one machine to process corresponding operations, while the machine in the in-use stage is a dummy machine.
- Control wafers are classified into three grades.
- Control wafers with particle numbers of less than 100 in 1 m^3 are classed grade one, less than 500 in 1 m^3 are grade two, and less than 1000 in 1 m^3 are grade three.
- The safety inventory is set to 0 for loop 1 and to 1 lot for loop 2 and loop 3.
- The releasing batch size for control wafers is one lot.

- The dispatching rule adopted is first-in, first-out (FIFO).

3. Control wafers inventory management system

This paper develops an MCW algorithm to estimate the most appropriate WIP level of control wafers for each grade. The proposed algorithm can be divided into two phases: (1) calculating new control wafers arrival rate, downgrade ratio and re-entrant ratio, and (2) estimating control wafers cycle time and WIP level for each grade.

The multi-loop system presented here can supply new control wafers in the 1st loop and downgrade control wafers to the j th loop ($1 < j$). When supply and demand are in balance, we can calculate the new control wafers supply rate, the re-entrant control wafers arrival rate and the downgrade control wafers arrival rate. The cycle time for each grade of control wafers is calculated by adding up the downgrade waiting time, the re-entrant waiting time and the PUR process time for each grade of control wafers. The WIP level for each grade of control wafers is obtained by multiplying the arrival rate (consisting of new control wafers arrival and downgrade arrival)

and cycle time of control wafers. The estimation procedures for the two phases are depicted in figure 4 and described in the next section.

3.1 Calculation of downgrade and re-entrant ratios

The multi-loop system of control wafers is constructed by the downgrade and PUR process procedures. In the j th loop, the supply and depletion of control wafers continue repeatedly, and a balanced production and exhaustion multi-loop system is adequate to solve control wafer problems. In figure 2, when the j th loop declares a need of control wafers, control wafers can be supplied from the pre-disposition stage. The pre-disposition stage (X_{j1}) supplies downgraded control wafers to meet the demand. If the downgraded control wafers are not sufficient to meet the demand, the first loop can pull new control wafers for use. However, for other loops, downgraded control wafers will be pulled from upper grade. In a stabilized system, the arrival rate of control wafers is equal to the leaving rate of control wafers. The relationship between re-entrant arrival ratio and downgrading arrival ratio can be found in Chung *et al.* (2004).

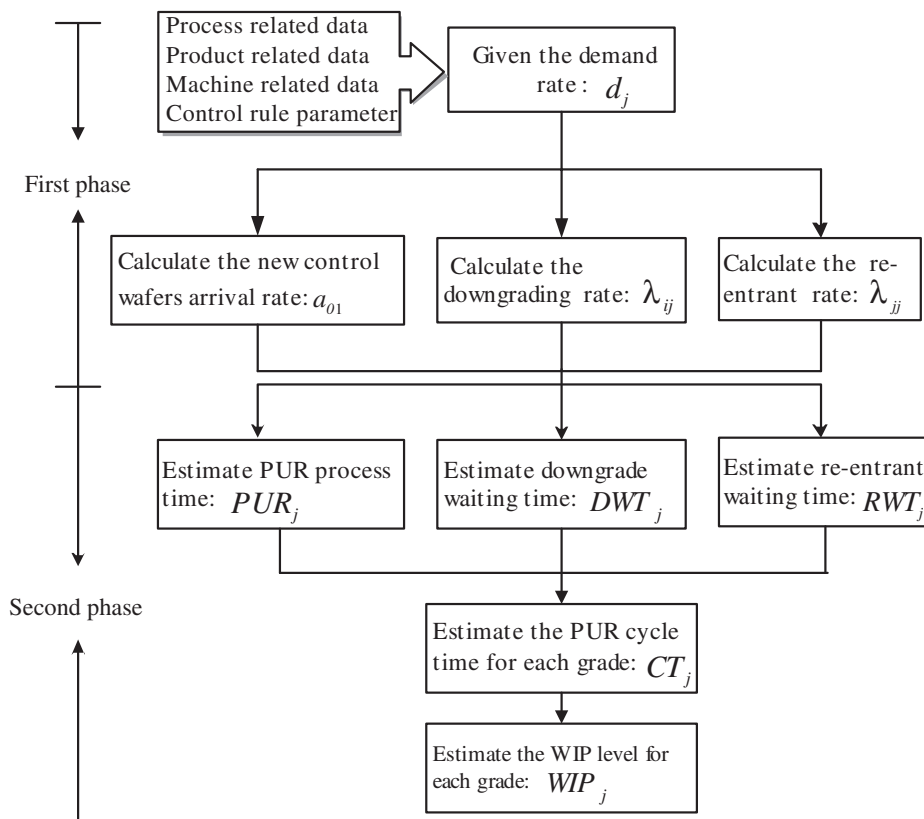


Figure 4. Flow process of the MCW algorithm.

The multi-loop system must supply enough control wafers for use in time, and shortage is not allowed. The operative constraints are as follows. By equation (1), the demand rate of control wafers is equal to the supply rate of control wafers for each loop. In the first loop, the supply rate of control wafers is equal to the new arrival rate of control wafers and the re-entrant rate, and this relationship is shown in equation (2). For other loops, the supply rate of control wafers is equal to the control wafers re-entrant rate and down-grade rates from up-stream loops, as shown in equation (3). The constraints are as follows:

$$d_j = \lambda_j \quad j = 1, 2, \dots, c. \tag{1}$$

$$\lambda_j = a_{01} + \lambda_1 P_{1j} \quad j = 1. \tag{2}$$

$$\lambda_j = \sum_{i=1}^j \lambda_i P_{ij} \quad j = 2, \dots, c. \tag{3}$$

where d_j is the demand rate of control wafers per day, λ_j is the supply (arrival) rate of control wafers per day, a_{01} is the supply rate of new control wafers per day, P_{ij} ($i=j$) is the re-entrant ratio and P_{ij} ($i < j$) is the downgrading ratio.

3.2 Estimation of cycle time and WIP level

The cycle time of control wafers is defined to be the time interval from control wafers entering the j th loop system to leaving the j th loop system. Cycle time consists of downgrading waiting time, re-entrant waiting time and process time. They are defined as follows:

1. *The downgrading waiting time:* DWT_j . The downgrading waiting time is the time interval between downgrade arriving of control wafers and the pre-disposition of PUR process in loop j . In the first loop, new control wafers are pulled, and no downgrading waiting time is required. For loop 2 and loop 3, control wafers have to be pulled from the upper grade, not from new control wafers. The downgrading waiting time can be obtained by deducting the interval time ($1/\lambda_j$) from the average downgrading arrival time of the upper grade ($1/\lambda_j \times (1 - P_{jj})$):

$$DWT_j = \begin{cases} 0 & j = 1 \\ \frac{1}{\lambda_j \times (1 - P_{jj})} - \frac{1}{\lambda_j} & j = 2, \dots, c \end{cases} \tag{4}$$

where $\lambda \times (1 - P_{jj})$ is equal to the sum of downgrading arrival rate ($\sum_{i=1}^{j-1} \lambda_{ij}$).

2. *The re-entrant waiting time:* RWT_j . The re-entrant waiting time is caused from control wafers

re-entrant arriving to in-use in the PUR process in loop j . The difference between re-entrant arrival time and in-use time is multiplied by the number of repeat times to estimate the re-entrant waiting time:

$$RWT_j = \left(\frac{k}{\lambda_j} - \frac{1}{\mu_{j1}} - \frac{1}{\mu_{j2}} - \frac{1}{\mu_{j3}} \right) \times \frac{P_{jj}}{1 - P_{jj}} \quad j = 1, 2, \dots, c \tag{5}$$

where λ_j is the total arrival rate of the j th loop, μ_{jr} is the r th service rate of the j th loop, P_{jj} is re-entrant ratio of the j th loop

$$\text{as } 0 \leq \frac{1}{\mu_{j1}} + \frac{1}{\mu_{j2}} + \frac{1}{\mu_{j3}} \leq \frac{1}{\lambda_j} \quad k = 1$$

$$\frac{1}{\lambda_j} \leq \frac{1}{\mu_{j1}} + \frac{1}{\mu_{j2}} + \frac{1}{\mu_{j3}} \leq \frac{2}{\lambda_j} \quad k = 2$$

⋮

$$\frac{n-1}{\lambda_j} \leq \frac{1}{\mu_{j1}} + \frac{1}{\mu_{j2}} + \frac{1}{\mu_{j3}} \leq \frac{n}{\lambda_j} \quad k = n.$$

3. *Theoretical process time:* PUR_j . The theoretical process time includes the PUR process time, loading and unloading time of control wafers in loop j . Process time is obtained by multiplying process service time by the number of repeat times.

$$PUR_j = \frac{1}{\mu_{j1}} \times \frac{1}{1 - P_{jj}} + \frac{1}{\mu_{j2}} \times \frac{1}{1 - P_{jj}} + \frac{1}{\mu_{j3}} \times \frac{P_{jj}}{1 - P_{jj}} \quad j = 1, 2, \dots, c. \tag{6}$$

Cycle time for each loop j , CT_j , equals the sum of DWT_j , RWT_j and PUR_j ($CT_j = DWT_j + RWT_j + PUR_j$) and is calculated by equation (7):

$$CT_j = \begin{cases} \frac{1}{\mu_{j1}} \times \frac{1}{1 - P_{jj}} + \frac{1}{\mu_{j2}} \times \frac{1}{1 - P_{jj}} + \frac{1}{\mu_{j3}} \times \frac{P_{jj}}{1 - P_{jj}} + \left(\frac{k}{\lambda_j} - \frac{1}{\mu_{j1}} - \frac{1}{\mu_{j2}} - \frac{1}{\mu_{j3}} \right) \times \frac{P_{jj}}{1 - P_{jj}} & j = 1 \\ \frac{1}{\mu_{j1}} \times \frac{1}{1 - P_{jj}} + \frac{1}{\mu_{j2}} \times \frac{1}{1 - P_{jj}} + \frac{1}{\mu_{j3}} \times \frac{P_{jj}}{1 - P_{jj}} + \left(\frac{k}{\lambda_j} - \frac{1}{\mu_{j1}} - \frac{1}{\mu_{j2}} - \frac{1}{\mu_{j3}} \right) \times \frac{P_{jj}}{1 - P_{jj}} + \left(\frac{1}{\lambda_j \times (1 - P_{jj})} - \frac{1}{\lambda_j} \right) & j = 2, \dots, c. \end{cases} \tag{7}$$

The WIP level of a loop can be estimated by equations (8) and (9). The WIP level of loop j is

$$WIP_j = \lambda_j \times (1 - P_{jj}) \times CT_j \quad j = 1, 2, \dots, c \quad (8)$$

$$\lambda_j \times (1 - P_{jj}) = \begin{cases} a_{01} & j = 1 \\ \sum_{i=1}^{j-1} \lambda_{ij} & j = 2, \dots, c \end{cases} \quad (9)$$

where WIP_j is the work-in-process in the j th loop and CT_j is the cycle time of the j th loop. The system WIP level, WIP_s , of control wafers is as follows:

$$WIP_s = \sum_{j=1}^c WIP_j. \quad (10)$$

3.3 Algorithm procedures

The procedures of the MCW algorithm are as follows:

Step 1. By equation (1) to (3), given the demand rate ($d_j = \lambda_j$), re-entrant arrival ratio P_{jj} and downgrading arrival ratio P_{ij} , calculate the new control wafers arrival rate a_{01} , re-entrant arrival rate λ_{ij} and downgrading arrival rate λ_{ij} for each loop j .

Step 2. By equation (7), calculate cycle time (CT_j) of control wafers for the j th loop.

Step 3. By equations (8) and (9), calculate WIP level of control wafers for the j th loop.

Step 4. By equation (10), calculate WIP level of control wafers for the system.

4. Numerical example and simulation results

In order to justify the applicability of the proposed MCW algorithm, we consider some cases to investigate the effects of different demand rates on the system. We compare our estimated parameter values with the results obtained from simulations by eM-Plant simulation programming software (Teconmatix Technologies Ltd. 2000). The simulation horizon is set to 110 days, in which the first 10 days are a warm up period. In order to eliminate simulation errors, simulations with different seeds are run ten times, and the average value of simulation results is used as the comparison object.

4.1 Basic system input

To investigate the effects of planning on the management system, actual data is taken from a wafer fabrication factory located on the Science-Based Industrial

Table 1. The service rate for each process (unit: day).

Loop j	u_{j1}	u_{j2}	u_{j3}
$j=1$	144	18	24
$j=2$	288	16	20
$j=3$	192	24	24

Park in Hsinchu, Taiwan. The basic information is as follows:

1. *Demand rate.* In the photolithography area, there are three grades of control wafers in the process. The demand rate per day for each grade ($d_j, j=1, 2, 3$) is given.
2. *PUR process.* In each loop j , the in-use service is the bottleneck. The service rates are shown in table 1.
3. *Machine data for the control wafers.* The distribution of the mean time between failures (*MTBF*), the mean time to repairs (*MTTR*), the mean time between preventive maintenance (*MTBPM*) and the mean time to preventive maintenance (*MTTPM*) for each work station are known.

4.2 Numerical example

The cycle time of loop 1 with different demand rates and re-entrant ratios under MCW algorithm and simulation are compared in table 2. The WIP level of loop 1 with different demand rates and re-entrant ratios by two methods are compared in table 3. Tables 4–7 show the information for other loops. The relationship of cycle time, demand rate and re-entrant ratio for loop 1 under MCW algorithm is depicted in figure 5, and that for simulation is shown in figure 6. The relationship of WIP level, demand rate and re-entrant ratio for loop 1 under MCW algorithm is depicted in figure 7, and that for simulation is shown in figure 8.

Figures 5 and 6 show very similar graphs obtained from MCW algorithm and from a simulation. When re-entrant ratio (P_{11}) increases in loop 1, the cycle time of control wafers in the loop increases too; thus, a positive relationship between the two factors is present. Next, when demand rate (d_j) increases, a greater number of control wafers are demanded, and the cycle time of control wafers in the loop decreases. From table 2, we can notice that the greatest difference in cycle times among different demand rates is ($1.5 - 1.5 = 0$) when $P_{11} = 0$, and the greatest difference in cycle times is ($44.7 - 25.5 = 22.2$) when $P_{11} = 0.9$. From table 4, we can notice that the greatest difference in cycle times

Table 2. The cycle time of 1st loop under MCW and simulation with demand rate = 10(1)18 and re-entrant ratio = 0.0(0.1)0.9 (unit: hour).

Demand rate		Ratio									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
10	MCW	1.500	2.033	2.700	3.557	4.700	6.300	8.700	12.700	20.700	44.700
	Simulation	1.517	2.051	2.798	3.575	4.643	6.306	8.062	12.572	20.608	44.316
	D.R. (%)	-1.121	-0.861	-3.503	-0.500	1.228	-0.095	7.914	1.018	0.446	0.867
11	MCW	1.500	1.985	2.591	3.370	4.409	5.864	8.045	11.682	18.955	40.773
	Simulation	1.517	2.001	2.708	3.442	4.525	5.869	8.047	11.917	18.883	40.455
	D.R. (%)	-1.121	-0.807	-4.324	-2.088	-2.562	-0.091	-0.019	-1.973	0.379	0.785
12	MCW	1.500	1.944	2.500	3.214	4.167	5.500	7.500	10.833	17.500	37.500
	Simulation	1.517	1.962	2.597	3.247	4.233	5.496	7.502	11.188	17.442	37.234
	D.R. (%)	-1.121	-0.895	-3.735	-1.008	-1.567	0.073	-0.027	-3.170	0.333	0.714
13	MCW	1.500	1.910	2.423	3.082	3.962	5.192	7.038	10.115	16.269	34.731
	Simulation	1.517	1.927	2.517	3.086	4.007	5.197	7.032	10.404	16.221	34.503
	D.R. (%)	-1.121	-0.869	-3.732	-0.116	-1.135	-0.090	0.092	-2.774	0.297	0.660
14	MCW	1.500	1.881	2.357	2.969	3.786	4.929	6.643	9.500	15.214	32.357
	Simulation	1.517	1.917	2.447	2.961	3.889	4.933	6.645	9.628	15.176	32.162
	D.R. (%)	-1.121	-1.880	-3.672	0.283	-2.656	-0.090	-0.032	-1.329	0.252	0.607
15	MCW	1.500	1.856	2.300	2.871	3.633	4.700	6.300	8.967	14.300	30.300
	Simulation	1.517	1.862	2.378	2.888	3.618	4.704	6.303	8.918	14.268	30.130
	D.R. (%)	-1.121	-0.346	-3.280	-0.574	0.424	-0.085	-0.048	0.546	0.224	0.564
16	MCW	1.500	1.833	2.250	2.786	3.500	4.500	6.000	8.500	13.500	28.500
	Simulation	1.517	1.851	2.336	2.805	3.564	4.501	6.002	8.621	13.475	28.350
	D.R. (%)	-1.121	-0.954	-3.682	-0.688	-1.796	-0.022	-0.033	-1.404	0.186	0.529
17	MCW	1.500	1.814	2.206	2.710	3.382	4.324	5.735	8.088	12.794	26.912
	Simulation	1.517	1.828	2.282	2.735	3.433	4.323	5.731	8.273	12.773	26.778
	D.R. (%)	-1.121	-0.781	-3.336	-0.911	-1.475	0.012	0.075	-2.233	0.165	0.500
18	MCW	1.500	1.796	2.167	2.643	3.278	4.167	5.500	7.722	12.167	25.500
	Simulation	1.517	1.813	2.241	2.651	3.309	4.167	5.502	7.881	12.151	25.381
	D.R. (%)	-1.121	-0.921	-3.317	-0.307	-0.944	-0.008	-0.036	-2.015	0.129	0.469

*The discrepancy ratio, D.R. (%), is defined as: (MCW result - simulation result)/(simulation result) × 100%.

among different demand rates is (1.583 - 1.583 = 0) when $P_{22} = 0$, and the greatest difference in cycle times is (66.383 - 42.083 = 24.3) when $P_{22} = 0.9$. From table 6, we can notice that the greatest difference in cycle times among different demand rates is (1.125 - 1.125 = 0) when $P_{33} = 0$, and the greatest difference in cycle times is (38.69 - 37.125 = 1.565) when $P_{33} = 0.9$. This means that when the re-entrant ratio gets smaller, the cycle times among different demand rates will be closer.

Figures 7 and 8 show the relationship among re-entrant ratio, demand rate and WIP level. When the re-entrant ratio (P_{11}) increases in loop 1, the WIP level of control wafers in that loop also increases. When the demand rate (d_i) increases, the WIP level in the loop also increases. Therefore, a positive relationship is found both between re-entrant ratio and WIP level, and between demand rate and WIP level. Table 3 shows that the greatest difference in WIP levels among different demand rates is (1.125 - 0.625 = 0.5) when $P_{11} = 0$, and the greatest difference in WIP levels is (1.913 - 1.863 = 0.05) when $P_{11} = 0.9$. From table 5, we can see that the greatest difference in WIP levels among different

demand rates is (1 - 0.625 = 0.375) when $P_{22} = 0$, and the greatest difference in WIP levels is (2.8 - 2.763 = 0.037) when $P_{22} = 0.9$. Table 7 also shows that the greatest difference in WIP levels among different demand rates is (1.125 - 1.078 = 0.047) when $P_{33} = 0$, and the greatest difference in WIP levels is (3.713 - 3.708 = 0.005) when $P_{33} = 0.9$. This indicates that when the re-entrant ratio gets bigger, the WIP levels among different demand rates will be closer.

The relationships of the above factors for loop 2 and 3 also show that the results obtained from the MCW algorithm and from simulation are pretty similar.

4.3 Result analysis

The results of the MCW algorithm are compared with those of simulation. As shown in tables 2-7, the absolute percentage of discrepancy in cycle time estimation is between 0.008% and 4.324% among all cases in loop 1, between 0.005% and 1.227% in loop 2, and between 0.002% and 1.489% in loop 3. The absolute percentage

Table 3. The WIP level of 1st loop under MCW and simulation with demand rate = 10(1)18 and re-entrant ratio = 0.0(0.1)0.9 (unit: lot).

Demand rate		Ratio									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
10	MCW	0.625	0.763	0.900	1.038	1.175	1.313	1.450	1.588	1.725	1.863
	Simulation	0.624	0.762	0.899	1.037	1.174	1.311	1.447	1.584	1.719	1.847
	D.R. (%)	0.096	0.079	0.100	0.058	0.085	0.107	0.235	0.253	0.349	0.867
11	MCW	0.688	0.819	0.950	1.081	1.213	1.344	1.475	1.606	1.738	1.869
	Simulation	0.687	0.818	0.949	1.081	1.212	1.343	1.472	1.603	1.732	1.854
	D.R. (%)	0.087	0.079	0.063	0.060	0.074	0.086	0.204	0.228	0.318	0.785
12	MCW	0.750	0.875	1.000	1.125	1.250	1.375	1.500	1.625	1.750	1.875
	Simulation	0.749	0.874	0.999	1.124	1.249	1.374	1.497	1.622	1.745	1.862
	D.R. (%)	0.080	0.069	0.060	0.053	0.064	0.073	0.180	0.203	0.287	0.714
13	MCW	0.813	0.931	1.050	1.169	1.288	1.406	1.525	1.644	1.763	1.881
	Simulation	0.812	0.931	1.049	1.168	1.287	1.405	1.524	1.641	1.758	1.869
	D.R. (%)	0.074	0.070	0.057	0.056	0.062	0.068	0.098	0.186	0.262	0.661
14	MCW	0.875	0.988	1.100	1.213	1.325	1.438	1.550	1.663	1.775	1.888
	Simulation	0.874	0.987	1.099	1.212	1.324	1.437	1.548	1.660	1.771	1.876
	D.R. (%)	0.069	0.061	0.055	0.050	0.053	0.056	0.142	0.175	0.243	0.608
15	MCW	0.938	1.044	1.150	1.256	1.363	1.469	1.575	1.681	1.788	1.894
	Simulation	0.937	1.043	1.149	1.256	1.362	1.468	1.573	1.679	1.784	1.883
	D.R. (%)	0.064	0.062	0.052	0.052	0.051	0.051	0.127	0.158	0.224	0.566
16	MCW	1.000	1.100	1.200	1.300	1.400	1.500	1.600	1.700	1.800	1.900
	Simulation	0.999	1.099	1.199	1.299	1.398	1.498	1.598	1.698	1.796	1.890
	D.R. (%)	0.120	0.118	0.100	0.092	0.136	0.127	0.119	0.147	0.212	0.524
17	MCW	1.063	1.156	1.250	1.344	1.438	1.531	1.625	1.719	1.813	1.906
	Simulation	1.062	1.156	1.249	1.343	1.436	1.529	1.624	1.716	1.809	1.897
	D.R. (%)	0.057	0.056	0.048	0.048	0.125	0.121	0.074	0.137	0.193	0.498
18	MCW	1.125	1.213	1.300	1.388	1.475	1.563	1.650	1.738	1.825	1.913
	Simulation	1.124	1.211	1.299	1.386	1.473	1.561	1.648	1.735	1.822	1.904
	D.R. (%)	0.098	0.091	0.085	0.079	0.115	0.109	0.097	0.127	0.181	0.468

Table 4. The cycle time of loop 2 under MCW and simulation with demand rate = 10(1)16 and re-entrant ratio = 0.0(0.1)0.9 (unit: hour).

Demand rate		Ratio									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
10	MCW	1.583	2.383	3.383	4.669	6.383	8.783	12.383	18.383	30.383	66.383
	Simulation	1.601	2.401	3.401	4.683	6.383	8.777	12.349	18.303	30.015	65.881
	D.R. (%)	-1.103	-0.736	-0.519	-0.298	0.005	0.072	0.278	0.439	1.227	0.762
11	MCW	1.583	2.311	3.220	4.389	5.947	8.129	11.402	16.856	27.765	60.492
	Simulation	1.601	2.328	3.233	4.402	5.952	8.124	11.374	16.794	27.574	60.076
	D.R. (%)	-1.103	-0.747	-0.411	-0.306	-0.085	0.059	0.242	0.370	0.693	0.693
12	MCW	1.583	2.250	3.083	4.155	5.583	7.583	10.583	15.583	25.583	55.583
	Simulation	1.601	2.267	3.101	4.170	5.589	7.581	10.563	15.533	25.425	55.234
	D.R. (%)	-1.103	-0.750	-0.570	-0.365	-0.101	0.031	0.192	0.324	0.623	0.632
13	MCW	1.583	2.199	2.968	3.957	5.276	7.122	9.891	14.506	23.737	51.429
	Simulation	1.601	2.217	2.985	3.972	5.283	7.119	9.877	14.467	23.603	51.131
	D.R. (%)	-1.103	-0.825	-0.571	-0.379	-0.139	0.039	0.142	0.272	0.568	0.584
14	MCW	1.583	2.155	2.869	3.787	5.012	6.726	9.298	13.583	22.155	47.869
	Simulation	1.601	2.172	2.887	3.803	5.022	6.724	9.298	13.554	22.027	47.613
	D.R. (%)	-1.103	-0.794	-0.622	-0.410	-0.201	0.033	-0.004	0.216	0.580	0.538
15	MCW	1.583	2.117	2.783	3.640	4.783	6.383	8.783	12.783	20.783	44.783
	Simulation	1.601	2.133	2.807	3.653	4.797	6.382	8.777	12.758	20.685	44.560
	D.R. (%)	-1.103	-0.766	-0.843	-0.343	-0.285	0.021	0.072	0.199	0.475	0.501
16	MCW	1.583	2.083	2.708	3.512	4.583	6.083	8.333	12.083	19.583	42.083
	Simulation	1.601	2.103	2.727	3.525	4.595	6.075	8.325	12.063	19.505	41.888
	D.R. (%)	-1.103	-0.935	-0.685	-0.371	-0.254	0.137	0.100	0.169	0.402	0.466

Table 5. The WIP level of loop 2 under MCW and simulation with demand rate = 10(1)16 and re-entrant ratio = 0.0(0.1)0.9 (unit: lot).

Demand rate		Ratio									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
10	MCW	0.625	0.863	1.100	1.338	1.575	1.813	2.050	2.288	2.525	2.763
	Simulation	0.650	0.894	1.128	1.362	1.595	1.829	2.060	2.290	2.526	2.745
	D.R. (%)	-3.846	-3.523	-2.482	-1.770	-1.229	-0.880	-0.485	-0.122	-0.040	0.638
11	MCW	0.688	0.919	1.150	1.381	1.613	1.844	2.075	2.306	2.538	2.769
	Simulation	0.716	0.953	1.181	1.408	1.634	1.862	2.087	2.311	2.540	2.754
	D.R. (%)	-3.967	-3.634	-2.608	-1.893	-1.340	-0.969	-0.561	-0.201	-0.087	0.554
12	MCW	0.750	0.967	1.183	1.400	1.617	1.833	2.050	2.267	2.483	2.700
	Simulation	0.788	1.013	1.234	1.454	1.674	1.895	2.113	2.331	2.553	2.762
	D.R. (%)	-4.810	-4.555	-4.075	-3.727	-3.436	-3.254	-3.000	-2.777	-2.744	-2.234
13	MCW	0.813	1.031	1.250	1.469	1.688	1.906	2.125	2.344	2.563	2.781
	Simulation	0.848	1.072	1.286	1.500	1.714	1.928	2.140	2.352	2.567	2.770
	D.R. (%)	-4.175	-3.810	-2.830	-2.109	-1.540	-1.133	-0.706	-0.342	-0.175	0.421
14	MCW	0.875	1.088	1.300	1.513	1.725	1.938	2.150	2.363	2.575	2.788
	Simulation	0.914	1.132	1.339	1.547	1.754	1.961	2.167	2.372	2.581	2.777
	D.R. (%)	-4.256	-3.889	-2.920	-2.211	-1.631	-1.208	-0.771	-0.405	-0.213	0.364
15	MCW	0.938	1.144	1.350	1.556	1.763	1.969	2.175	2.381	2.588	2.794
	Simulation	0.980	1.191	1.392	1.593	1.793	1.994	2.193	2.392	2.594	2.785
	D.R. (%)	-4.327	-3.959	-3.010	-2.301	-1.718	-1.281	-0.834	-0.462	-0.251	0.314
16	MCW	1.000	1.200	1.400	1.600	1.800	2.000	2.200	2.400	2.600	2.800
	Simulation	1.045	1.250	1.444	1.638	1.832	2.025	2.220	2.413	2.607	2.793
	D.R. (%)	-4.334	-3.977	-3.054	-2.314	-1.725	-1.230	-0.896	-0.518	-0.284	0.269

Table 6. The cycle time of loop 3 under MCW and simulation with demand rate = 23(1)24, and re-entrant ratio = 0.0(0.1)0.9 (unit: hour).

Demand rate		Ratio									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
23	MCW	1.125	1.589	2.168	2.914	3.908	5.299	7.386	10.864	17.821	38.690
	Simulation	1.142	1.607	2.186	2.925	3.922	5.305	7.386	10.819	17.757	38.317
	D.R. (%)	-1.489	-1.135	-0.802	-0.382	-0.367	-0.115	-0.002	0.417	0.358	0.974
24	MCW	1.125	1.569	2.125	2.839	3.792	5.125	7.125	10.458	17.125	37.125
	Simulation	1.142	1.587	2.142	2.851	3.805	5.137	7.127	10.419	17.067	36.784
	D.R. (%)	-1.489	-1.106	-0.794	-0.411	-0.350	-0.234	-0.028	0.378	0.340	0.927

Table 7. The WIP level of loop 3 under MCW and simulation with demand rate = 23(1)24 and re-entrant ratio = 0.0(0.1)0.9 (unit: lot).

Demand rate		Ratio									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
23	MCW	1.078	1.370	1.663	1.955	2.247	2.539	2.831	3.123	3.416	3.708
	Simulation	1.078	1.370	1.663	1.954	2.246	2.538	2.829	3.121	3.413	3.696
	D.R. (%)	-0.007	0.001	0*	0.025	0.043	0.042	0.069	0.078	0.086	0.317
24	MCW	1.125	1.413	1.700	1.988	2.275	2.563	2.850	3.138	3.425	3.713
	Simulation	1.125	1.412	1.700	1.986	2.273	2.560	2.847	3.133	3.421	3.701
	D.R. (%)	0.027	0.021	0.024	0.060	0.079	0.090	0.091	0.150	0.120	0.303

*Denotes a value less than 0.001.

of discrepancy in WIP level for MCW and simulation is between 0.048% and 0.867% among all cases for loop 1, between 0.040% and 4.810% in loop 2, and between 0 and 0.317% in loop 3. The system WIP level is the sum

of WIP level for each loop, and the WIP level for a single loop can be obtained with the given demand rate and re-entrant ratio. The absolute percentage of discrepancy in system WIP level under MCW and

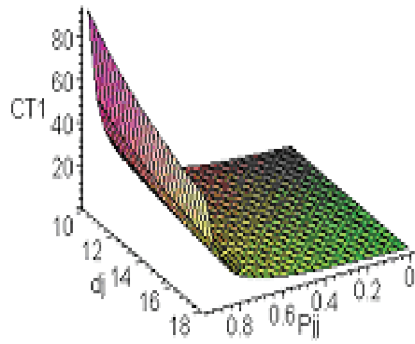


Figure 5. The cycle time of 1st loop under MCW with demand rate = 10(1)18 and re-entrant ratio = 0.0(0.1)0.9.

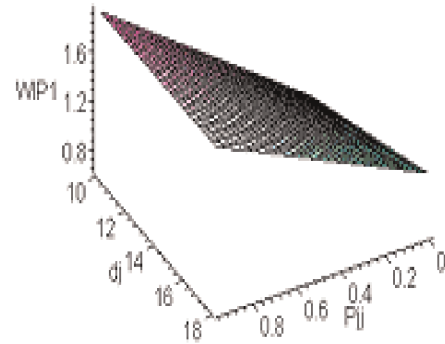


Figure 7. The WIP level of 1st loop under MCW with demand rate = 10(1)18 and re-entrant ratio = 0.0(0.1)0.9.

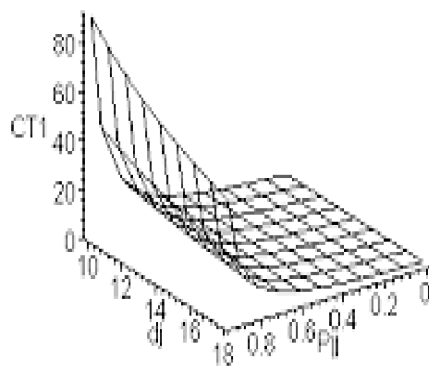


Figure 6. The cycle time of 1st loop under simulation with demand rate = 10(1)18 and re-entrant ratio = 0.0(0.1)0.9.

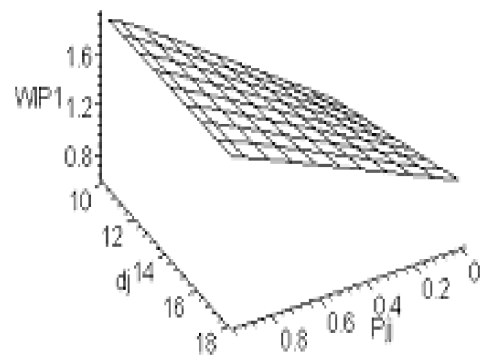


Figure 8. The WIP level of 1st loop under simulation with demand rate = 10(1)18 and re-entrant ratio = 0.0(0.1)0.9.

simulation is less than 5%. Based on the above analysis, we can see that the proposed MCW algorithm performs quite well in estimating cycle time and WIP level for each control wafers grade.

5. Conclusions

In most wafer fabrications today, the WIP level of control wafers is set to 30–50% of that for normal products, with 30% being the benchmark as indicated by Lin (2000). As the WIP level of control wafers increases, the capacity for processing normal products decreases. However, without the necessary control wafers utilization, the production process cannot be maintained effectively and the yield of product wafers is affected in consequence. In consequence, a decision must be made to minimize the total control wafer costs and to determine the optimal inventory level of control wafers while maintaining the same level of production throughput.

Control wafers inventory management is a challenge to wafer fabrication, and estimating depletion rate

correctly for each grade becomes an important task. Demand rate and WIP level of control wafers are closely related to many factors such as throughput target, product mix and priority mix. In this paper, the MCW algorithm is proposed to estimate the control wafers WIP level for each grade. By estimating processing time, downgrading waiting time, and re-entrant waiting time for each PUR process, cycle time and WIP level for each grade can be determined. From the results obtained in the example, the MCW algorithm showed a promising performance estimating the depletion rate and WIP level. The percentage of discrepancy in system WIP level between the MCW algorithm and simulation result is less than 5%. The results showed that the proposed methodology is very accurate.

Future research could focus on different depletion cost for each grade of control wafers, to find the minimum cost curve as well as to achieve manufacturer's planning target. In this research, only one machine is present in each work station, and how the model should be constructed under the environment of multiple machines in work stations is our future research direction.

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