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Predicting Due Dates under Various Combinations of Scheduling Rules in a Wafer Fabrication Factory

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Abstract. In a wafer fabrication factory, the completion time of an order is affected by many factors related to the specifics of the order and the status of the system, so is difficult to predict precisely. The level of influence of each factor on the order completion time may also depend on the production system characteristics, such as the rules for releasing and dispatching. This paper presents a method to identify those factors that significantly impact upon the order completion time under various combinations of scheduling rules. Computer simulations and statistical analyses were used to develop effective due date assignment models for improving the due date related performances. The first step of this research was to select the releasing and dispatching rules from those that were cited so frequently in related wafer fabrication factory researches. Simulation and statistical analyses were combined to identify the critical factors for predicting order completion time under various combinations of scheduling rules. In each combination of scheduling rules, two efficient due date assignment models were established by using the regression method for accurately predicting the order due date. Two due date assignment models, called the significant factor prediction model (SFM) and the key factor prediction model (KFM), are proposed to empirically compare the due date assignment rules widely used in practice. The simulation results indicate that SFM and KFM are superior to the other due date assignment rules. The releasing rule, dispatching rule and due date assignment rule have significant impacts on the due date related performances, with larger improvements coming from due date assignment and dispatching rules than from releasing rules.

Keywords: wafer fabrication factory, releasing rules, dispatching rules, due date assignment rules.

1. INTRODUCTION

The semiconductor manufacturing industry is one of the most important industries in Taiwan. Manufacturing processes for integrated circuits consist of four basic steps (Kim *et al.*, 1998): wafer fabrication, wafer probe, assembly (packaging) and final testing. Wafer fabrication is the most technologically complex of these four steps, as well as the most time-consuming phase. Hundreds of operations are required to produce a complete wafer. Controlling the production system on the shop floor is a very demanding task due to the complicated manufacturing

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process and re-entrant characteristics. It is crucial that the wafer fabrication process to meet the demands of customers.

Previous research on wafer fabrication shop floor control usually measured the throughput, cycle time, work in process and the utilization of bottleneck machines. Now, in addition to these above performance measures, we also need to provide accurate order due dates to enhance customer satisfaction.

In order to provide a more accurate order due date, the ability to predict the order completion time must be possible. In general, order completion time is affected by many factors, which are all related to the order characteristics and the status of the system at that time. The level of influence of each factor on the order completion time may depend on the production system characteristics, such as the releasing and dispatching rules used.

The objective of this paper is to identify the factors that significantly effect the order completion time under various combinations of the releasing and the dispatching rules. Computer simulations and statistical analyses are used to identify these factors and develop due date assignment models.

In the following section, related work on wafer fabrication scheduling is discussed. Section 3 will present the system under study and the assumptions made. Section 4 will discuss the experimental results and analysis. Finally, section 5 presents the conclusions from this research.

2. PREVIOUS RELATED WORK

A list of shop floor control strategies commonly used in wafer fabrication is shown in Table 1. Glassey and Resende (1988), Lou and Kager (1989), Wein (1988), Yan *et al.* (1996) developed a new releasing rule and validated that it could improve the system performance of a wafer fabrication factory. Fowler *et al.* (1997), Glassey and Resende (1988), Hsieh *et al.* (1999), Lu *et al.* (1994), Chung and Hunag (1999) integrated releasing and dispatching rules to improve system performance. Kim *et al.* (1998) and Lee and Chen (1997) used various combinations of releasing rule and dispatching rule to improve the system's performance with a settled due-date assignment rule. Most of the previous research on wafer fabrication focused on the releasing rule or the dispatching rule without considering the due date assignment rule. There is no current research that is focused on designing appropriate due date assignment rules under the various combinations of scheduling rules. Although meeting the customer order due date is currently more important than it ever was in the past, due date performance measures have not been used very often (Kim *et al.*, 1998). Ahmed and Fisher (1992) proved that an interaction existed between the releasing rule, dispatching rule and the due date assignment rule. Therefore, designing a superior due date assignment rule must involve the information about the releasing and dispatching rules used.

3. SIMULATION MODEL

The simulation model developed in this study is based on a wafer fabrication factory in the Hsinchu Science-Industrial Park, Taiwan. There are three products in the simulation model. The product mix is 20% product 1, 35% product 2 and 45% product 3. The numbers of circuit layers are 15 for product 1, 18 for product 2 and 17 for product 3.

The model consists of 53 single-server or multi-server workstations. In each workstation, the dispatching rule is determining the next job to be processed in the workstation.

If more than one machine is available at the same time for processing a particular job, one of the available machines is chosen at random. The bottleneck workstation is the photolithographic exposure station. At this station, wafers on which photoresist is deposited are exposed to ultraviolet light through a mask, a glass plate holding a pattern for a single layer of circuits (Kim *et al.*, 1998).

There are four workstations involved batch processing. The Minimum Batch Size (MBS) rule and the First Come Fist Served (FCFS) rule are used in this simulation model for the batching and dispatching in these workstations. In the MBS rule, processing is started when the number of waiting lots at these four workstations is greater than, or equal to, two.

The transfer time between workstations is ignored in this model. The inter-arrival times of orders are generated from an exponential distribution with a mean of 40 min. The arrival rate was determined using a preliminary experiment in which the bottleneck workstation utilization was nearly 100%. A lot contains 24 wafers. The processing time for a lot of product i at workstation j is randomly generated from a uniform distribution with a range of $(0.95p_{ij}, 1.05p_{ij})$.p_{ij} is the mean processing time for a lot of product i at workstation j, determined by using actual data from a real wafer fabrication factory. Setup time is included in the processing time.

Table 1. A list of the shop floor control strategies used in a wafer fabrication factory

Author (s)	Year	Number of products	Due date assignment rule	Releasing rule	Dispatching rule
Glassey *et al.*	1988	Single	Ignored	1. SA 2. UNIF 3. CONWIP 4. WR	1. SA+ 2. SRPT 3. FIFO 4. SPT
Glassey *et al*	1988	Single	Ignored	1. UNIF 2. WR 3. CONWIP 4. SA	1. SA+
Wein	1988	Single	Ignored	1. POISSON 2. DETERMIN 3. CONWIP 4. WR	1. FIFO 2. SRPT 3. FGCA 4. LWNQ/M 5. CYCLIC 6. FGCA/IMP 7. LTNV 8. STNV 9. FIFO+ 10. M1-M2 11. W(a,b) 12. SRPT+
Lou *et al*	1989	Single	Ignored	1. TB 2. UNIF	1. TB 2. FIFO
Lu *et al*	1994	Single	Ignored	1. POISSON 2. DETERMIN 3. CONWIP 4. WR	1. FSVCT 2. FSMCT 3. CYCLIC 4. LTNV 5. FIFO+ 6. FIFO 7. NexQL 8. FGCA 9. SRPT 10. EDD 11. STNV 12. M1-M2 13. W(a,b)
Yan *et al*	1996	Single	Ignored	1. TB 2. UNIF	1. TB 2. FIFO
Fowler *et al.*	1997	Single	ignored	1. UNIF 2. CONWIP	1. EDD 2. FIFO 3. CR
Lee *et al*	1997	Five	75% normal lot, 25% hot lot	1. UL 2. CONWIP	1. FIFO 2. SPT 3. SRPT 4. EDD 5. SLACK 6. CR
Kim *et al*	1998	Five	$d_k=a_k+P_k*U(25,30)$	When to release 1. WR Which one to release 1. MODEP 2. COVERT 3. MOD 4. ATC 5. EDD 6. SLACK 7. MSEC2	1. MODEP 2. COVERT 3. MOD 4. ATC 5. EDD 6. SLACK 7. MSEC2
Hsieh *et al.*	1999	Single	ignored	1. DETERMIN 2. CONWIP 3. WR	1. FSMCT 2. FSVCT 3. LDF 4. OSA 5. FIFO
Chung *et al.*	1999	Six	ignored	1. SA+ 2. SA 3. WC 4. CONWIP 5. FIFO	1. SA+ 2. SA 3. WC 4. EDD 5. FIFO

The simulation model takes into account downtime, which includes unscheduled breakdowns. The MTBF and MTTR values for each workstation were randomly generated from exponential distributions with given mean values.

3.1 Selection of Releasing Rules

The classification structures of the releasing rule and the dispatching rule were examined in order to select those rules commonly used in related research. For the classification structure of the releasing rule, we modified the classification dimensions proposed by Bergamaschi *et al.* (1997).

Bergamaschi *et al.* (1997) considered eight main dimensions that described the fundamental principles, characteristics and logic of existing releasing rules used in a job shop system. We used only the first three dimensions to classify the releasing rules. These three dimensions are:

1. Order release mechanism: The order releasing rules can be classified into two major types, depending upon the mechanism that triggers the release of one or more orders: load limited methodologies and time phased methodologies. Under the load-limited methodology, orders are released to the shop based upon their specific features and the existing workload in the shop. The time phased order release approach is centered on computing a release time for each order and then letting orders enter the shop when that predetermined time is reached, regardless of the actual shop load at that time.
2. Timing convention: The timing convention of an order-releasing rule determines when an order release can take place. According to the information from the reviewed literature, the timing convention may be either continuous or discrete. Under the continuous timing convention a release may occur at any time during the system's operation. Under the discrete timing convention, an order release procedure may occur only at periodic intervals (e.g. the beginning of each shift, day or week)
3. Workload measure aggregation: Under the load limited order release system, the workload can be stated in various levels of aggregation. At one extreme is the total shop load that gives no indication of the way the load is distributed among the different work centers in the shop. An alternative approach is to compute and control the workload for selected bottleneck work centers only. Another way is to compute the load separately at each work center.

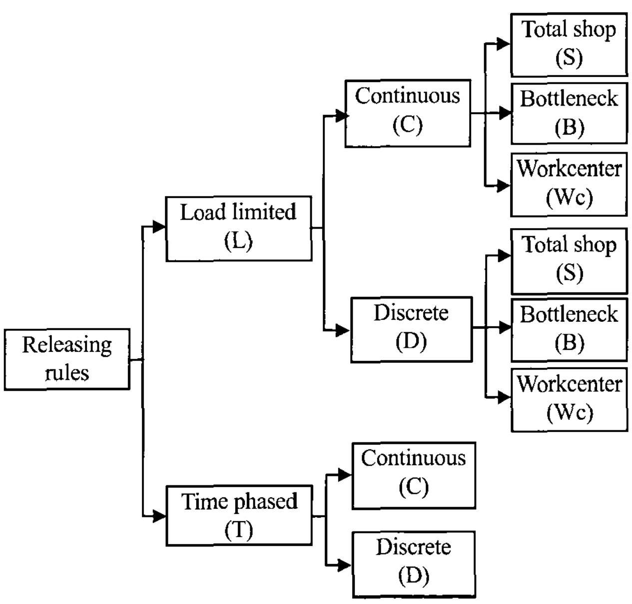

Figure 1. Classification structure of releasing

The classification structure of the releasing rule is presented in Figure 1. There are eight categories of releasing rules that include LDB, LDS, LDWc, LCS, LCB, LCWc, TD, and TC. According to the structure in Figure 1, we attempted to classify the releasing rules shown on Table 1 systematically, and counted the total number of citations in the previous literatures. The result is presented in Table 2.

Releasing rules that had a higher number of citations in each category were used in this research. TB, CONWIP, WR, SA, UNIF and POISSON rules were chosen. None of the releasing rules were in the LDS, LDWc and LCWc categories. After surveying other production systems, Melynk and Ragatz (1989) proposed that the WCEDD rule is better than some simple releasing rules in WIP, mean tardiness and average queue length. The WCEDD rule was classified to the LCWc category. For the sake of comparison we included it with the other rules.

3.2 Selection of Dispatching Rules

The dispatching rule classification structure is based on the structure developed by Blackstone et al. (1982). In their research, dispatching rules were classified into the following four categories:

1. Rules involving processing time (PT oriented)
2. Rules involving due dates (due date oriented)
3. Simple rules involving neither processing time nor due dates (simple)
4. Rules involving two or more of the first three categories (combined)

There are some load oriented dispatching rules that were used in related research (NexQL, SA+, SA, WC, and TB). These rules cannot be explicitly classified into the previous categories. Hence, we added a new category to the original classification structure.

5. Rules involving the load status (load oriented)

Similarly, we attempted to classify the dispatching rules shown on Table 1 systematically and counted the total number of citations. The classification result is presented in Table 3. The dispatching rules used in our study were those that had a higher total number of citations in each category. SRPT, EDD, FIFO, CR, COVERT, SA, TB and NexQL.

3.3 Methodology

Due date assignment rules can be divided into two classes: exogenous and endogenous. This paper focused on the "Endogenous" rules. Using an endogenous due date assignment, the production system must predict the completion time for an order so as to meet the expected due date for the customer. In general, the order completion time can be represented by the following formula (1) (Chang, 1994):

$$f_i = r_i + p_i + q_i \tag{1}$$

f_i: completion time for order i
r_i: arrival time for order i
p_i: sum of the processing time for all operations for order i
q_i: total queuing time in the system for order i

Table 2. The releasing rule tabulation results

Category	authors / rules	Wein (1988)	Chung (1999)	Kim (1998)	Glassey (1988)	Lu (1994)	Lee (1997)	Hsieh (1999)	Yan (1996)	Lou (1989)	Glassey (1988)	Fowler (1997)	Total cites
L-D-B	TB[1]								ˇ	ˇ			2
	WC		ˇ										1
L-D-S													
L-D-Wc													
L-C-S	CONWIP[2]	ˇ	ˇ		ˇ	ˇ	ˇ	ˇ			ˇ	ˇ	8
L-C-B	WR[3]	ˇ		ˇ	ˇ	ˇ		ˇ			ˇ		6
	SA[4]		ˇ		ˇ						ˇ		3
	SA+		ˇ										1
L-C-Wc	WCEDD[5]												
T-D	UNIF[6]				ˇ		ˇ		ˇ	ˇ	ˇ	ˇ	6
	DETERMIN	ˇ				ˇ		ˇ					3
T-C	POISSON[7]	ˇ				ˇ							2

1. If the *actual output of first layer < expected output* and *actual inventory of first layer< predetermined inventory level*, the job will be a candidate. The candidates have the largest value of *weight of product × difference in output* will be released.
2. Regulating new wafer releases to maintain a constant number of lots in the production system
3. Regulating new wafer releases to maintain a constant amount of expected work at a bottleneck station
4. A new wafer lot is released to avoid starvation of a bottleneck workstation
5. Regulating new wafer releases to maintain their predetermined WIP level of main workstations.
6. Release a new lot into the fab at a constant rate, e.g. 16 lot/per-day
7. New wafer releases time are randomly generated from Poisson distribution

Table 3. The dispatching rule tabulation result

Category	authors / Rules	Wein (1988)	Chung (1999)	Kim (1998)	Glassey (1988)	Lu (1994)	Lee (1997)	Hsieh (1999)	Yan (1996)	Lou (1989)	Glassey (1988)	Fowler (1997)	Total cites
PT oriented	LTNV	ˇ				ˇ							2
	STNV	ˇ				ˇ							2
	M1-M2	ˇ				ˇ							2
	SRPT[1]	ˇ			ˇ	ˇ	ˇ				ˇ		5
	SPT						ˇ				ˇ		2
	MOD			ˇ									1
	ATC			ˇ									1
Load oriented	NexQL[2]					ˇ							1
	SA+		ˇ										1
	SA[3]		ˇ								ˇ		2
	WC		ˇ										1
	TB[4]								ˇ	ˇ			2
	W(a,b)	ˇ				ˇ							2
Combined	CR[5]						ˇ					ˇ	2
	FSVCT					ˇ		ˇ					2
	FSMCT					ˇ		ˇ					2

Table 3. The dispatching rule tabulation result (cont.)

Category	Rules \ authors	Wein (1988)	Chung (1999)	Kim (1998)	Glassey (1988)	Lu (1994)	Lee (1997)	Hsieh (1999)	Yan (1996)	Lou (1989)	Glassey (1988)	Fowler (1997)	Total cites
Combined	SLACK			ˇ			ˇ						2
	FIFO+	ˇ											1
	MODEP			ˇ									1
	COVERT[6]			ˇ									1
	LDF							ˇ					1
	OSA							ˇ					1
	MSEC2			ˇ									1
	SRPT+	ˇ											1
Due date oriented	EDD[7]		ˇ	ˇ		ˇ	ˇ					ˇ	5
Simple	FIFO[8]	ˇ	ˇ			ˇ	ˇ		ˇ	ˇ	ˇ	ˇ	8
	CYCLIC	ˇ				ˇ							2
	FGCA	ˇ				ˇ							2
	FGCA/IMP	ˇ											1

1. Shortest total remaining processing time
2. The lot whose queue at the next station it will visit has the least amount of expected work per machine will be assigned high priority.
3. Assign high priority to jobs that are close to the bottleneck station and/or that contribute a large amount of work content to the station
4. If the actual output of each layer < expected output and actual inventory of each layer < predetermined inventory level, the job will be a candidate. The candidates have the largest value of weight of product × weight of layers × difference in output will be assigned high priority.
5. Smallest CR, CR = (due date-total remaining PT-present date) / total remaining PT
6. Largest C, C = delaying cost/total remaining PT
7. Earliest due date
8. First in first out

r_i and p_i are known constants after the order *i* arrives. The total queuing time for order (q_i) is the only variable that needs to be estimated for predicting f_i in formula (1). Hence, the manager must establish an applicable prediction model for q_i to precisely predict the completion time for the new orders. In its general form q_i consists of two major parts. First, q_{psp} is the time from order acceptance to order release into the shop. Second, q_s is the total queue time from order release into the shop to order completion. Providing a precise order due date is a valuable tool for improving customer satisfaction. In order to quote an accurate and precise due date for the customer, the manager must establish precise prediction models for q_s and q_{psp}.

To assign a due date for order *i* in a dynamic system, most research included one or more factors in a regression model for predicting the order due date. In this study, 92 factors were considered, and are listed in Appendix A. These 92 factors can be classified into three main classes: (1) information about shop conditions, (2) information about order characteristics, and (3) information about the pre shop pool condition. There are some subclasses in classes (1) and (3). The factors in class (1) can be divided into four subclasses: (1-1) information about the shop status, (1-2) information about the bottleneck resource status, (1-3) information about the constraint resource status, and (1-4) information about recently completed orders. The factors in class (3) can be divided into two subclasses: (3-1) information about the pre shop pool status (3-2) and information about orders due to be completed soon. The classification structure of the prediction factors is shown in Table 4.

The objectives of this study are: (1) identify the factors that have significant effects on the order completion time in a wafer fabrication factory under every combination of scheduling rules and (2) using the factor that significantly affects the on the job queuing time, build two due date assignment models (i.e. key factor prediction model (KFM), and a significant factor prediction model (SFM)) for each combination of scheduling rules. Our due-date prediction models are divided into two parts, one for predicting the queuing time q_s, and another for predicting q_{psp}.

Table 4. Classification of the prediction factors

Main class	Subclass	Number of factors included
Shop condition (1)	shop status (1-1)	8
	bottleneck resource status (1-2)	10
	constraint resource status (1-3)	50
	Recently completed orders (1-4)	8
Order characteristics (2)	———	8
Pre shop pool condition (3)	pre shop pool status (3-1)	4
	Recently completed orders (3-2)	4

The prediction model for q_s was built by choosing one or more significant factors from main classes 1 and 2. The prediction model for q_{PSP} was constructed by choosing one or more significant factors from main classes 1, 2, and 3. Our procedure for designing due date assignment rules was as follows:

1. Execute prior runs for 44 combinations of releasing and dispatching rules (dispatching rules SA, TB combined only with releasing rules SA, TB); we can then collect 44 data sets in the virtual fab. A data set consists of 92 variances and real flow time for each lot (containing the processing time and actual waiting time in the PSP and shop). These data sets were used for constructing the regression model. It is necessary to guarantee statistical independence among the data before the test is performed. To insure this, only one in every 10 outputs from the shop simulation was randomly selected to be included in the sample of 1000 jobs. The simulation was designed for a simulation time period of 24 hours a day, and the data was collected after 150 warm days.

2. The forward selection procedure was applied to identify the factors that significantly affected q_s, q_{psp} in each data set. The procedures of forward selection are (Sen and Srivastava, 1990): start with no variable in the model and first select x_j which has the highest correlation with y. Subsequent selections are based on partial correlations, given that the variables are already selected. At each step, the partial F-value is computed for the variable just selected, given that the variables previously selected are already in the model. If this sequential F-value falls below an α-point, the variable is deleted and another one is sought. If no suitable variable is found or if all the variables are in the model, the procedure stops.

3. In each data set, construction of the q_s and q_{psp} prediction regression models using the factor that most significantly affected q_s and q_{psp} is the key factor prediction model (KFM). The KFM model is shown in formula (2). d_i, r_i, and p_i denote the due date, arrival time and total processing time for order i, respectively. $q^{(a,b)}_{KFM(S)}(i)$ denotes the expected queuing time in the shop for order i by using the regression model that included the factor that most significantly affected q_s in the combination of releasing rule a and dispatching rule b. $q^{(a,b)}_{KFM(PSP)}(i)$ denotes the expected queuing time in the pre-shop pool for order i by using the regression model that included the factor that most significantly affected q_{psp} in the combination of releasing rule a and dispatching rule b.

$$d_i = r_i + p_i + q^{(a,b)}_{KFM(S)}(i) + q^{(a,b)}_{KFM(PSP)}(i) \quad (2)$$

4. Use the factors that significantly affected on q_s and q_{psp} to construct the significant factor prediction model (SFM). The SFM rule is shown in formula (3). $q^{(a,b)}_{SFM(S)}(i)$ denotes the expected queuing time in the shop for order i, predicted by using the regression model that included the factors that significantly affected q_s under the combination of releasing rule a and dispatching rule b. $q^{(a,b)}_{SFM(PSP)}(i)$ denotes the expected queuing time in the pre-shop pool for order i, predicted by using the regression model that included the factors that significantly affected q_{psp} under the combination of releasing rule a and dispatching rule b.

$$d_i = r_i + p_i + q^{(a,b)}_{SFM(S)}(i) + q^{(a,b)}_{SFM(PSP)}(i) \quad (3)$$

The following rules were constructed for benchmarking purposes.

1. Total work content due date rule (TWK): This method assigns due dates to each order as a multiple of the order's total processing time. TWK is widely used in practice. The TWK rule is as follows:

$$di = r_i + k * p_i \quad (4)$$

where d_i denotes the assigned due date for order i, and k is the parameter that reflects the expected queue time that order i will experience in the system. The k values are estimated based on the following regression models:

$$f_i = k * P_i \quad (5)$$

where f_i denotes the completion time for order i. Similarly, 44 TWK rules were developed to respond to 44 scheduling rule combinations.

2. Random allowance due date rule (RDM): This method assigns due dates to each order by an external customer. In practice, the average cycle time from

order acceptance to order completion is within a 30 to 60 day range (Chen *et al.*, 2000). Hence, all orders are given a random flow allowance generated from a uniform distribution with a range (30, 60). The RDM rule is as follows:

$$d_i = r_i + U(30,60) \tag{6}$$

To compare the performance of our SFM and KFM with the other two rules, four different kinds of performance measures were used (Chang, 1994):

1. Mean absolute missed due date (MAMD), which measures the average absolute difference between the actual completion dates and the promised due dates for orders. This method was used as the primary performance measure. A smaller MAMD value implies a better due date prediction capability. MAMD is always equal to the sum of the mean earliness (ME) and mean tardiness (MT).

$$MAMD = \sum_{i=1}^{n} [\max(0, d_i - f_i) + \max(0, f_i - d_i)] / n \tag{7}$$

2. Mean assigned flow time (MAFT) is the average expected flow time for orders. A smaller MAFT value is better because it means shorter quoted delivery dates for the orders.

$$MAFT = \sum_{i=1}^{n} (d_i - r_i) / n \tag{8}$$

3. Mean Earliness (ME)

$$ME = \sum_{i=1}^{n} \max(0, d_i - f_i) / n \tag{9}$$

4. Mean Tardiness (MT)

$$MT = \sum_{i=1}^{n} \max(0, f_i - d_i) / n \tag{10}$$

f_i : Completion time of order i
d_i : Due date of order i
r_i : Arrival time of order i
n : Sample sizes

4. EXPERIMENTAL RESULTS

By conducting 44 prior experiments, we constructed the KFM and SFM due-date assignment models. Among these models, the KFM models that were constructed in each combination of scheduling rules are shown in Table 5. In Table 5, each KFM model consists of two regression prediction models, one for predicting the queuing time in the shop, the other one for predicting the queuing time in the pre-shop pool.

Table 5. Factor that most significantly affected the q_s, q_{psp} for each combination of scheduling rules

Combination of scheduling rules	Queuing time	KFM model
WR-FIFO	q_S	13.579+14 024*VAR 78
	q_{PSP}	0.04437+0.988*VAR89
WR-EDD	q_S	18.333+16.48*VAR82
	q_{PSP}	1.358+0.0557*VAR85
WR-CR	q_S	-6.247+3.096*VAR77
	q_{PSP}	0.103+0.982*VAR89
WR-NexQL	q_S	-5.866+27.723*VAR78
	q_{PSP}	1.062+0.05428*VAR85
WR-SRPT	q_S	22.111+0.101*VAR32
	q_{PSP}	0.830+0.06125*VAR85
WR-COVERT	q_S	-7.005+3.43*VAR77
	q_{PSP}	0.141+0.06159*VAR8 5
CONWIP-FIFO	q_S	18.307+13.39*VAR78
	q_{PSP}	0.105+0.05893*VAR85
CONWIP-EDD	q_S	29.547+13 041*VAR82
	q_{PSP}	0.05562+0.0519*VAR85
CONWIP-CR	q_S	32.893+10.775*VAR82
	q_{PSP}	0.05363+0.153*VAR87
CONWIP-NexQL	q_S	-11.811+35.868*VAR78
	q_{PSP}	0.221+0.05079*VAR85
CONWIP-SRPT	q_S	37.833-0.327*VAR10
	q_{PSP}	0.04239+0.05059*VAR85
CONWIP-COVERT	q_S	50.59-0.433*VAR75
	q_{PSP}	0.01891+0.125*VAR88
SA-FIFO	q_S	16.947+0.02922*VAR18
	q_{PSP}	1.349+0.109*VAR88
SA-EDD	q_S	9.891+0.106*VAR66
	q_{PSP}	0.523+0.04667*VAR85
SA-CR	q_S	36.989-0.402*VAR10
	q_{PSP}	-2.17+0.4*VAR10
SA-NexQL	q_S	31.928+0.717*VAR1 0
	q_{PSP}	13.873-0.0594*VAR 10
SA-SRPT	q_S	42.143-1.399*VAR13
	q_{PSP}	1.182+0.09821*VAR88
SA-COVERT	q_S	19.524+0.006054*VAR8
	q_{PSP}	14.795-0.00566*VAR8
SA-SA	q_S	185.113-114.543*VAR78
	q_{PSP}	18.68-0.00355*VAR2
UNIF-FIFO	q_S	22.423+0.114*VAR65
	q_{PSP}	0.392+0.988*VAR69
UNIF-EDD	q_S	25.373+15.135*VAR82
	q_{PSP}	0.398+0.982*VAR69
UNIF-CR	q_S	-1.028+3.311*VAR77
	q_{PSP}	0.386+1.006*VAR69

Table 5. Factor that most significantly affected the q_s, q_{psp} for each combination of scheduling rules (cont.)

Combination of scheduling rules	Queuing time	KFM model
UNIF-NexQL	q_S	1.064+26.43*VAR78
	q_{PSP}	0.381+1.028*VAR69
UNIF-SRPT	q_S	-9.488+0.309*VAR64
	q_{PSP}	0.39+0 983*VAR69
UNIF-COVERT	q_S	32.311+11.774*VAR82
	q_{PSP}	0.427+0.985*VAR69
POI-FIFO	q_S	15.165+18 608*VAR78
	q_{PSP}	0.0458+0.0614*VAR85
POI-EDD	q_S	28 422+21.867*VAT82
	q_{PSP}	0.04916+0.05999*VAR85
POI-CR	q_S	-3.288+3 653*VAR77
	q_{PSP}	0.05658+0 05882*VAR85
POI-NexQL	q_S	15.198+0.005286*VAR2
	q_{PSP}	0.04535+0.0619*VAR85
POI-SRPT	q_S	-15.474+0.206*VAR4
	q_{PSP}	0.05336+0.06028*VAR85
POI-COVERT	q_S	-2.143+3.448*VAR77
	q_{PSP}	0.04919+0.05668*VAR85
TB-FIFO	q_S	8.008+0.149*VAR65
	q_{PSP}	51.52-31.829*VAR84
TB-EDD	q_S	16.25-0.0104*VAR6
	q_{PSP}	12.663+0.09881*VAR87
TB-CR	q_S	4.684+0.05485*VAR18
	q_{PSP}	0.714+0.05524*VAR85
TB-NexQL	q_S	29.024-0.217*VAR72
	q_{PSP}	-24.873+54.947*VAR80
TB-SRPT	q_S	14.577-0.323*VAR76
	q_{PSP}	104.217-57.671*VAR78
TB-COVERT	q_S	25.154+8.795*VAR82
	q_{PSP}	6.142+0.2*VAR13

Table 5. Factor that most significantly affected the q_s, q_{psp} for each combination of scheduling rules (cont.)

Combination of scheduling rules	Queuing time	KFM model
TB-TB	q_S	13.441+0.127*VAR64
	q_{PSP}	3.505+16.563*VAR81
WCEDD-FIFO	q_S	2.421+0.06584*VAR18
	q_{PSP}	0.426+0.887*VAR69
WCEDD-EDD	q_S	27.809+15.618*VAR82
	q_{PSP}	0.626+0.913*VAR69
WCEDD-CR	q_S	31.648+1.203*VAR84
	q_{PSP}	0.413+0 949*VAR69
WCEDD-NexQL	q_S	-104.836+13.294*VAR77
	q_{PSP}	0.398+0.957*VAR69
WCEDD-SRPT	q_S	2.35*0.135*VAR4
	q_{PSP}	0.431+0.961*VAR84
WCEDD-COVERT	q_S	-1.433+3.369*VAR77
	q_{PSP}	0.7-0.0363*VAR85

Also, we identified the class that contains the factor that most significantly affected q_s, q_{psp} for each combination of scheduling rules, as shown in Table 6.

In addition to the combinations of UNIF, TB, WCEDD and all dispatching rules, the most significant factor that affects the qpsp is either the number of lots in the pre shop pool or average waiting time (three lots) in the pre-shop-pool which had only just finished. The most significant factor that affects qs involves the order characteristics (2) under the combinations of WR, CONWIP, UNIF, POISSON, WCEDD and all dispatching rules. Under the combinations of SA, TB and all dispatching rules, the most significant factor is the variation from the dispatching rule used. As indicated in Table 5, there are only 7 out of 44 combinations of scheduling rules in which the most significant factor is the total processing time for the order. Hence, the TWK rules that are used widely in practice are in fact not suitable for all combinations of scheduling rules in practice.

Table 6. The main class of the most significant factor for each combination of scheduling rules

	WR		CONWIP		SA		UNIF		POISSON		TB		WCEDD	
	Shop	PSP	Shop	PSP	Shop	PSP	Shop	PSP	Shop	PSP	Shop	PSP	Shop	PSP
FIFO	(2)	(3-2)	(2)	(3-1)	(1-2)	(3-1)	(1-3)	(3-2)	(2)	(3-1)	(1-2)	(2)	(1-2)	(3-2)
EDD	(2)	(3-1)	(2)	(3-1)	(1-2)	(3-1)	(2)	(3-2)	(2)	(3-1)	(1-1)	(3-1)	(2)	(3-2)
CR	(2)	(3-2)	(2)	(3-1)	(1-2)	(1-2)	(2)	(3-2)	(2)	(3-1)	(1-2)	(3-1)	(2)	(3-2)
NexQL	(2)	(3-1)	(2)	(3-1)	(1-2)	(1-2)	(2)	(3-2)	(1-1)	(3-1)	(1-4)	(2)	(2)	(3-2)
SRPT	(1-3)	(3-1)	(1-2)	(3-1)	(1-2)	(3-1)	(1-3)	(3-2)	(1-1)	(3-1)	(1-4)	(2)	(1-1)	(3-2)
COVERT	(2)	(3-1)	(1-4)	(3-1)	(1-1)	(1-1)	(2)	(3-2)	(2)	(3-1)	(2)	(1-2)	(2)	(3-1)
SA					(2)	(1-1)								
TB											(1-3)	(2)		

(x-y) : (main class of due date predicting factor, subclass of due date predicting factor)

At the same time, we summarized the number of factors that significantly affected q_s, q_{psp} in Table 7. In Table 7, most factors that related to shop conditions were included in the prediction model.

There are 176 treatments, each with a specific combination of dispatching, releasing, and due date assignment rules. There were 1056 simulation runs with 6 runs for each treatment.

Table 7. Number of significant factors included in the SFM for each combination of scheduling rules

Combination of scheduling rules		Main class		
		1	2	3
WR-FIFO	q_S	5	2	0
	q_{PSP}	8	0	2
WR-EDD	q_S	10	1	0
	q_{PSP}	6	0	4
WR-CR	q_S	5	1	0
	q_{PSP}	7	0	3
WR-NexQL	q_S	2	2	0
	q_{PSP}	8	0	2
WR-SRPT	q_S	3	1	0
	q_{PSP}	8	0	2
WR-COVERT	q_S	9	2	0
	q_{PSP}	7	0	3
CONWIP-FIFO	q_S	6	2	0
	q_{PSP}	8	0	2
CONWIP-EDD	q_S	11	1	0
	q_{PSP}	8	0	2
CONWIP-CR	q_S	9	2	0
	q_{PSP}	8	0	2
CONWIP-NexQL	q_S	3	2	0
	q_{PSP}	6	1	3
CONWIP-SRPT	q_S	3	1	0
	q_{PSP}	7	0	3
CONWIP-COVERT	q_S	12	1	0
	q_{PSP}	6	0	4
SA-FIFO	q_S	10	1	0
	q_{PSP}	6	0	2
SA-CR	q_S	14	1	0
	q_{PSP}	8	0	2
SA-NexQL	q_S	11	1	0
	q_{PSP}	8	0	2
SA-SRPT	q_S	3	0	0
	q_{PSP}	6	0	2
SA-COVERT	q_S	14	1	0
	q_{PSP}	9	0	1
SA-SA	q_S	6	2	0
	q_{PSP}	9	0	1

Table 7. Number of significant factors included in the SFM for each combination of scheduling rules (cont.)

Combination of scheduling rules		Main class		
		1	2	3
UNIF-FIFO	q_S	7	2	0
	q_{PSP}	3	0	2
UNIF-EDD	q_S	7	2	0
	q_{PSP}	3	0	2
UNIF-CR	q_S	8	1	0
	q_{PSP}	4	0	2
UNIF-NexQL	q_S	1	3	0
	q_{PSP}	6	0	2
UNIF-SRPT	q_S	3	1	0
	q_{PSP}	0	1	2
UNIF-COVERT	q_S	7	1	0
	q_{PSP}	3	0	2
POI-FIFO	q_S	4	1	0
	q_{PSP}	4	1	1
POI-EDD	q_S	12	1	0
	q_{PSP}	5	0	3
POI-CR	q_S	10	1	0
	q_{PSP}	3	1	2
POI-NexQL	q_S	3	3	0
	q_{PSP}	3	0	2
POI-SRPT	q_S	5	1	0
	q_{PSP}	3	0	1
POI-COVERT	q_S	4	3	0
	q_{PSP}	3	0	4
TB-FIFO	q_S	9	1	0
	q_{PSP}	7	2	1
TB-EDD	q_S	13	0	0
	q_{PSP}	3	1	2
TB-CR	q_S	12	1	0
	q_{PSP}	7	1	2
TB-NexQL	q_S	5	1	0
	q_{PSP}	5	2	1
TB-SRPT	q_S	6	1	0
	q_{PSP}	5	1	2
TB-COVERT	q_S	10	1	0
	q_{PSP}	4	1	3
TB-TB	q_S	3	0	0
	q_{PSP}	3	1	1
WCEDD-FIFO	q_S	7	2	0
	q_{PSP}	3	0	3
WCEDD-EDD	q_S	10	1	0
	q_{PSP}	8	1	1
WCEDD-CR	q_S	8	3	0
	q_{PSP}	5	0	3
WCEDD-NexQL	q_S	7	2	0
	q_{PSP}	8	0	2
WCEDD-SRPT	q_S	4	0	0
	q_{PSP}	4	0	2
WCEDD-COVERT	q_S	11	2	0
	q_{PSP}	5	0	2

After running the 150 warm day simulations, information was collected on the four performance measures (MAMD, ME, MT, and MAFT) for the next 3000 orders. The experimental results are shown in Table 8. For every combination of scheduling rules, ranks were given to the due date assignment rules based on the performance measure values, with a higher rank given for the smaller value. Based on the results in Table 8, the large standard deviation in total queuing time (q_s+q_{psp}) in the system caused poor performances for MAMD, MT and ME. This is consistent with the conclusion of Chang (1994). The SFM, KFM rules perform better than the TWK and RDM rules as a primary performance measure for MAMD in most treatments. For the performance of MT and ME, the KFM and SFM rules perform better than the TWK and RDM rules in almost all treatments.

A three factor full-factorial design was used in this experiment to study the performance of the four due date assignment rules. The first factor was the due date assignment rule with four levels (based on rules KFM, SFM, TWK and RDM). The second factor was the dispatching rule with eight levels (SRPT, EDD, FIFO, CR, COVERT, SA, TB and NexQL). The third factor was the releasing rule with seven levels (TB, CONWIP, WR, SA, UNIF, POISSON and WCEDD). As indicated by the statistics shown in Table 9, all three main factors and their interactions had significant effects on all performance measures, except for the interaction of releasing rule and due date assignment rule on MT and MAMD.

The major objective of this research was to design appropriate due date assignment models for each combination of scheduling rules. The due date assignment rules were found to significantly effective for all performance measures. Hence, finding the optimal due date assignment rule for each combination of scheduling rules was necessary. The Duncan's multiple range test result for the due date assignment rules under every combination of releasing rule and dispatching rule are shown in Table 10. Based on the MAMD results in Table 10, the following observations can be made: (1) SFM and KFM rules performed better than the TWK and RDM rules in 15 combinations of scheduling rules; (2) significant difference exist only between the SFM and KFM rules, under the WR/CR, CONWIP/CR, SA/CR, SA/COVERT and POISSON/SRPT combinations, where the first and second terms in each parentheses denote rules for the releasing and the dispatching respectively.

For the MT performance, the due date assignment rule performance depended upon the releasing and dispatching rules. There were significant differences between the SFM, KFM and TWK rules, under the WR/CR, WR/SRPT, SA/CR, SA/COVERT, POISSON/SRPT, POISSON/COVERT, TB/CR, WCEDD/SRPT and WCEDD/COVERT combinations. The results show that when order due dates are assigned by external customers; there is no significant difference between the SFM, KFM and TWK rules on performance MT. The SFM, KFM and TWK rules performed better than the RDM rule in most treatments. For the ME performance, SFM and KFM rules perform better than the TWK and RDM rules in the 13 combinations of scheduling rules. Under the remaining combinations of scheduling rules, no significant differences existed between the SFM, KFM and TWK rules. For the MAFT performance, the RDM rule performed better than the SFM, KFM and TWK rules in 18 combinations of scheduling rules for performance measure MAFT. For the RDM rule, because the order due date is assigned by internal customers, the flow allowances would be assigned as short as possible. Otherwise, the performance of the SFM, KFM and TWK rules depend upon the releasing and dispatching rules used.

The releasing and dispatching rules were the two input variables in this research.

Table 8. Experimental results for the four performance measures

Releasing rule	Dispatching rule	Mean total queuing time	Standard deviation of total queuing time	Due date assignment rules	Performance measures			
					MAMD	MT	ME	MAFT
WR	FIFO	37.64	3.26	SFM	2.26 (2)	0.96 (2)	1.3 (2)	51.69 (4)
				KFM	2.13 (1)	0.92 (1)	1.21 (1)	51.64 (3)
				TWK	5.73 (3)	3.54 (3)	2.19 (4)	49.99 (2)
				RDM	10.66 (4)	8.48 (4)	2.17 (3)	45.02 (1)
	EDD	32.67	4.08	SFM	3.29 (2)	2.52 (2)	0.77 (1)	44.00 (1)
				KFM	2.99 (1)	1.91 (1)	1.09 (2)	44.94 (3)
				TWK	3.96 (3)	2.52 (2)	1.45 (3)	44.69 (2)
				RDM	8.44 (4)	4.59 (4)	3.85 (4)	45.02 (4)
	CR	35.38	1.40	SFM	0.93 (1)	0.21 (2)	0.72 (2)	46.01 (3)
				KFM	1.95 (2)	1.77 (3)	0.17 (1)	43.68 (1)
				TWK	2.69 (3)	0.08 (1)	2.61 (3)	47.86 (4)
				RDM	7.61 (4)	3.96 (4)	3.65 (4)	45.01 (2)

Table 8. Experimental results for the four performance measures (cont.)

Releasing rule	Dispatching rule	Mean total queuing time	Standard deviation of total queuing time	Due date assignment rules	Performance measures			
					MAMD	MT	ME	MAFT
WR	NexQL	38.57	4.94	SFM	3.26 (1)	1.74 (2)	1.52 (1)	48.18 (2)
				KFM	3.46 (2)	1.57 (1)	1.88 (2)	48.70 (3)
				TWK	4.45 (3)	1.95 (3)	2.50 (3)	48.94 (4)
				RDM	9.03 (4)	6.23 (4)	2.80 (4)	44.96 (1)
	SRPT	37.38	10.89	SFM	8.03 (2)	2.80 (2)	5.24 (2)	45.94 (3)
				KFM	7.49 (1)	3.60 (3)	3.89 (1)	43.79 (1)
				TWK	10.04 (3)	1.77 (1)	8.27 (4)	50.00 (4)
				RDM	10.61 (4)	4.58 (4)	6.03 (3)	44.95 (2)
	COVERT	35.02	1.26	SFM	1.13 (1)	0.23 (2)	0.90 (1)	45.42 (2)
				KFM	1.63 (2)	0.36 (3)	1.27 (2)	45.60 (3)
				TWK	3.38 (3)	0.07 (1)	3.31 (3)	47.88 (4)
				RDM	7.60 (4)	3.60 (4)	4.00 (4)	45.03 (1)
CONWIP	FIFO	37.97	3.47	SFM	2.95 (2)	2.11 (3)	0.84 (1)	49.10 (2)
				KFM	2.61 (1)	1.47 (1)	1.15 (2)	50.06 (4)
				TWK	3.57 (3)	1.98 (2)	1.60 (3)	50.00 (3)
				RDM	9.21 (4)	7.30 (4)	1.91 (4)	44.99 (1)
	EDD	33.22	4.03	SFM	4.94 (1)	1.68 (1)	3.27 (3)	47.57 (4)
				KFM	5.14 (2)	2.99 (2)	2.14 (1)	45.12 (2)
				TWK	6.27 (3)	3.26 (3)	3.02 (2)	45.74 (3)
				RDM	9.62 (4)	5.31 (4)	4.31 (4)	44.97 (1)
	CR	35.85	1.94	SFM	1.03 (1)	0.25 (1)	0.79 (1)	46.40 (2)
				KFM	2.26 (2)	0.48 (2)	1.78 (2)	47.06 (3)
				TWK	3.74 (3)	0.81 (3)	2.93 (3)	47.87 (4)
				RDM	8.00 (4)	4.35 (4)	3.64 (4)	45.03 (1)
	NexQL	37.04	5.95	SFM	3.62 (1)	2.23 (1)	1.39 (1)	49.28 (2)
				KFM	3.88 (2)	2.28 (2)	1.60 (2)	49.44 (3)
				TWK	4.89 (3)	2.50 (3)	2.39 (4)	50.01 (4)
				RDM	9.78 (4)	7.47 (4)	2.31 (3)	44.96 (1)
	SRPT	30.93	13.72	SFM	10.67 (1)	6.01 (4)	4.65 (1)	40.93 (1)
				KFM	10.72 (2)	5.88 (3)	4.84 (2)	41.24 (2)
				TWK	11.26 (3)	4.97 (1)	6.29 (3)	43.60 (3)
				RDM	13.65 (4)	5.44 (2)	8.21 (4)	45.05 (4)
	COVERT	35.98	2.12	SFM	1.54 (1)	0.86 (1)	0.69 (1)	48.71 (4)
				KFM	1.98 (2)	1.16 (2)	0.83 (3)	48.46 (3)
				TWK	2.42 (3)	1.68 (3)	0.74 (2)	47.87 (2)
				RDM	8.45 (4)	6.07 (4)	2.38 (4)	45.09 (1)
SA	FIFO	36.64	3.87	SFM	4.12 (2)	2.48 (2)	1.65 (3)	47.82 (4)
				KFM	3.85 (1)	2.43 (1)	1.42 (2)	47.65 (3)
				TWK	5.58 (3)	4.77 (3)	0.81 (1)	44.69 (1)
				RDM	9.65 (4)	6.67 (4)	2.98 (4)	44.96 (2)
	EDD	29.77	4.42	SFM	5.40 (2)	4.40 (2)	1.00 (2)	41.79 (2)
				KFM	4.76 (1)	3.73 (1)	1.03 (3)	42.50 (3)
				TWK	7.38 (3)	7.13 (4)	0.25 (1)	38.30 (1)
				RDM	9.17 (4)	4.68 (3)	4.49 (4)	45.01 (4)
	CR	34.75	1.07	SFM	1.13 (1)	0.49 (1)	0.64 (2)	47.08 (4)
				KFM	2.83 (2)	2.14 (2)	0.70 (3)	45.41 (3)
				TWK	4.43 (3)	4.36 (3)	0.07 (1)	42.56 (1)
				RDM	8.07 (4)	5.00 (4)	3.08 (4)	44.94 (2)
	NexQL	42.08	5.27	SFM	4.97 (2)	2.87 (1)	2.09 (2)	47.85 (3)
				KFM	4.95 (1)	2.95 (2)	2.00 (1)	47.69 (2)
				TWK	6.24 (3)	3.52 (3)	2.89 (4)	50.00 (4)
				RDM	8.98 (4)	6.32 (4)	2.66 (3)	44.98 (1)

Table 8. Experimental results for the four performance measures (cont.)

Releasing rule	Dispatching rule	Mean total queuing time	Standard deviation of total queuing time	Due date assignment rules	Performance measures			
					MAMD	MT	ME	MAFT
SA	SRPT	32.37	13.14	SFM	9.54 (1)	4.95 (2)	4.59 (2)	43.57 (2)
				KFM	9.67 (3)	5.20 (3)	4.47 (1)	43.19 (1)
				TWK	9.63 (2)	4.44 (1)	5.20 (3)	44.68 (3)
				RDM	12.10 (4)	5.53 (4)	6.57 (4)	44.97 (4)
	COVERT	34.88	1.40	SFM	1.20 (1)	0.28 (1)	0.93 (3)	49.76 (4)
				KFM	3.82 (3)	3.61 (3)	0.21 (1)	45.61 (2)
				TWK	2.91 (2)	2.03 (2)	0.88 (2)	47.89 (3)
				RDM	8.49 (4)	6.26 (4)	2.23 (4)	44.98 (1)
	SA	33.19	16.91	SFM	11.14 (1)	7.74 (1)	3.40 (1)	43.54 (1)
				KFM	12.46 (2)	8.39 (3)	4.08 (2)	43.57 (2)
				TWK	14.04 (3)	8.14 (2)	5.89 (3)	45.63 (4)
				RDM	15.70 (4)	9.33 (4)	6.37 (4)	44.93 (3)
UNIF	FIFO	43.32	3.62	SFM	2.32 (1)	1.09 (1)	1.23 (2)	54.85 (3)
				KFM	2.79 (2)	1.50 (3)	1.29 (3)	54.52 (2)
				TWK	3.08 (3)	1.24 (2)	1.84 (4)	55.33 (4)
				RDM	11.19 (4)	10.49 (4)	0.70 (1)	44.93 (1)
	EDD	30.02	3.38	SFM	4.80 (1)	3.75 (1)	1.05 (2)	40.98 (2)
				KFM	5.40 (2)	4.74 (3)	0.67 (1)	40.62 (1)
				TWK	6.79 (3)	5.13 (4)	1.33 (3)	42.56 (3)
				RDM	8.89 (4)	4.29 (2)	4.60 (4)	45.00 (4)
	CR	35.08	1.52	SFM	1.10 (1)	0.33 (2)	0.78 (1)	45.57 (2)
				KFM	1.27 (2)	0.33 (2)	0.94 (2)	45.72 (3)
				TWK	3.04 (3)	0.09 (1)	2.95 (3)	47.88 (4)
				RDM	7.58 (4)	3.81 (4)	3.77 (4)	44.98 (1)
	NexQL	37.22	5.81	SFM	4.31 (1)	2.87 (2)	1.44 (1)	48.04 (3)
				KFM	4.50 (2)	3.03 (3)	1.47 (2)	47.91 (2)
				TWK	4.91 (3)	2.19 (1)	2.73 (4)	50.00 (4)
				RDM	9.69 (4)	7.09 (4)	2.60 (3)	44.97 (1)
	SRPT	30.55	12.58	SFM	10.13 (1)	5.59 (3)	4.54 (1)	43.26 (1)
				KFM	10.20 (2)	5.58 (2)	4.62 (2)	43.35 (2)
				TWK	10.39 (3)	5.54 (1)	4.85 (3)	43.62 (3)
				RDM	12.88 (4)	6.08 (4)	6.80 (4)	45.03 (4)
	COVERT	36.09	2.67	SFM	1.03 (1)	0.33 (2)	0.70 (1)	46.94 (3)
				KFM	1.13 (2)	0.42 (3)	0.72 (2)	46.77 (2)
				TWK	2.90 (3)	0.19 (1)	2.71 (3)	48.93 (4)
				RDM	7.73 (4)	4.55 (4)	3.18 (4)	45.01 (1)
POISSON	FIFO	40.48	3.68	SFM	2.39 (1)	1.15 (1)	1.24 (1)	51.58 (3)
				KFM	3.43 (2)	1.91 (3)	1.52 (2)	51.10 (2)
				TWK	4.00 (3)	1.15 (1)	2.85 (4)	53.19 (4)
				RDM	9.62 (4)	8.05 (4)	1.57 (3)	44.99 (1)
	EDD	34.36	4.57	SFM	4.40 (1)	2.17 (3)	2.24 (1)	42.97 (1)
				KFM	4.65 (2)	1.38 (2)	3.27 (2)	44.78 (2)
				TWK	5.70 (3)	0.90 (1)	4.81 (3)	46.80 (4)
				RDM	8.82 (4)	3.39 (4)	5.43 (4)	44.93 (3)
	CR	36.03	2.20	SFM	1.31 (1)	0.56 (2)	0.75 (1)	46.48 (2)
				KFM	2.02 (2)	0.78 (3)	1.24 (2)	46.65 (3)
				TWK	3.45 (3)	0.35 (1)	3.10 (3)	48.94 (4)
				RDM	7.85 (4)	4.54 (4)	3.31 (4)	44.94 (1)
	NexQL	37.56	6.27	SFM	5.08 (1)	3.62 (1)	1.45 (1)	51.32 (4)
				KFM	6.72 (2)	4.82 (2)	1.90 (2)	50.57 (3)
				TWK	7.67 (3)	5.57 (3)	2.10 (4)	50.02 (2)
				RDM	12.53 (4)	10.54 (4)	1.98 (3)	44.92 (1)

Table 8. Experimental results for the four performance measures (cont.)

Releasing rule	Dispatching rule	Mean total queuing time	Standard deviation of total queuing time	Due date assignment rules	Performance measures			
					MAMD	MT	ME	MAFT
POISSON	SRPT	36.67	17.19	SFM	12.20 (2)	6.26 (4)	5.94 (2)	41.92 (2)
				KFM	10.82 (1)	5.96 (3)	4.86 (1)	41.14 (1)
				TWK	13.91 (4)	3.08 (1)	10.83 (4)	49.99 (4)
				RDM	13.69 (3)	5.48 (2)	8.22 (3)	44.98 (3)
	COVERT	34.82	1.17	SFM	0.95 (1)	0.32 (2)	0.62 (2)	47.35 (3)
				KFM	1.23 (2)	1.20 (3)	0.02 (1)	45.54 (2)
				TWK	1.54 (3)	0.29 (1)	1.25 (3)	47.88 (4)
				RDM	7.73 (4)	4.78 (4)	2.95 (4)	45.00 (1)
TB	FIFO	35.17	7.52	SFM	8.74 (1)	7.31 (3)	1.43 (1)	44.84 (1)
				KFM	9.38 (2)	6.11 (1)	3.34 (3)	47.04 (3)
				TWK	10.35 (3)	7.01 (2)	3.27 (2)	47.88 (4)
				RDM	12.80 (4)	9.21 (4)	3.59 (4)	45.09 (2)
	EDD	38.04	6.01	SFM	3.95 (1)	2.50 (1)	1.46 (1)	51.57 (4)
				KFM	6.29 (2)	4.79 (3)	1.50 (2)	49.31 (2)
				TWK	6.70 (3)	4.11 (2)	2.58 (4)	51.07 (3)
				RDM	11.67 (4)	9.66 (4)	2.01 (3)	44.95 (1)
	CR	35.43	1.90	SFM	3.27 (1)	3.07 (3)	0.21 (1)	43.38 (1)
				KFM	4.08 (2)	0.56 (1)	3.52 (3)	49.14 (4)
				TWK	5.07 (3)	2.19 (2)	2.88 (2)	47.87 (3)
				RDM	8.37 (4)	4.78 (4)	3.59 (4)	44.99 (2)
	NexQL	32.18	9.42	SFM	7.76 (1)	6.66 (2)	1.10 (1)	42.22 (2)
				KFM	8.25 (2)	7.08 (3)	1.17 (2)	41.88 (1)
				TWK	9.44 (3)	6.27 (1)	3.17 (3)	44.68 (3)
				RDM	11.93 (4)	7.36 (4)	4.57 (4)	44.99 (4)
	SRPT	38.28	9.43	SFM	6.17 (1)	3.12 (1)	3.06 (3)	51.97 (4)
				KFM	7.26 (2)	5.01 (3)	2.25 (1)	48.27 (2)
				TWK	7.36 (3)	4.17 (2)	3.20 (4)	51.06 (3)
				RDM	11.68 (4)	9.33 (4)	2.35 (2)	45.05 (1)
	COVERT	35.67	2.11	SFM	1.16 (1)	0.48 (1)	0.68 (1)	50.44 (4)
				KFM	4.37 (2)	3.35 (2)	1.02 (2)	46.13 (2)
				TWK	5.54 (3)	3.36 (3)	2.17 (3)	48.94 (3)
				RDM	10.20 (4)	7.68 (4)	2.52 (4)	44.98 (1)
	TB	34.57	7.09	SFM	7.33 (1)	0.81 (1)	6.52 (3)	46.87 (3)
				KFM	7.82 (2)	1.76 (3)	6.06 (1)	45.96 (2)
				TWK	8.32 (3)	1.14 (2)	7.18 (4)	47.87 (4)
				RDM	9.55 (4)	3.18 (4)	6.37 (2)	45.02 (1)
WCEDD	FIFO	39.89	4.45	SFM	2.59 (1)	1.75 (3)	0.84 (1)	47.43 (2)
				KFM	2.68 (2)	1.22 (2)	1.45 (2)	48.59 (3)
				TWK	5.82 (3)	0.49 (1)	5.33 (4)	53.19 (4)
				RDM	8.63 (4)	5.98 (4)	2.65 (3)	45.02 (1)
	EDD	34.63	4.39	SFM	5.38 (1)	1.81 (1)	3.57 (2)	47.30 (3)
				KFM	6.86 (2)	4.31 (3)	2.55 (1)	43.79 (1)
				TWK	8.17 (3)	2.92 (2)	5.25 (4)	47.87 (4)
				RDM	10.56 (4)	5.55 (4)	5.00 (3)	44.99 (2)
	CR	35.10	1.28	SFM	1.21 (1)	0.56 (2)	0.65 (1)	46.22 (3)
				KFM	1.67 (2)	0.96 (3)	0.71 (2)	45.76 (2)
				TWK	2.66 (3)	0.39 (1)	2.27 (3)	47.88 (4)
				RDM	7.78 (4)	4.42 (4)	3.37 (4)	44.91 (1)

Table 8. Experimental results for the four performance measures (cont.)

Releasing rule	Dispatching rule	Mean total queuing time	Standard deviation of total queuing time	Due date assignment rules	Performance measures			
					MAMD	MT	ME	MAFT
WCEDD	NexQL	38.47	6.14	SFM	3.84 (1)	1.84 (1)	2.00 (2)	50.66 (3)
				KFM	5.10 (2)	3.28 (3)	1.82 (1)	49.04 (2)
				TWK	5.78 (3)	2.61 (2)	3.17 (4)	51.06 (4)
				RDM	10.38 (4)	7.95 (4)	2.42 (3)	44.98 (1)
	SRPT	36.87	17.47	SFM	10.59 (1)	4.61 (3)	5.98 (1)	43.95 (1)
				KFM	12.23 (2)	6.21 (4)	6.01 (2)	46.38 (3)
				TWK	13.27 (3)	2.91 (1)	10.36 (4)	50.03 (4)
				RDM	13.28 (4)	5.41 (2)	7.87 (3)	45.04 (2)
	COVERT	34.81	1.13	SFM	1.22 (1)	0.19 (1)	1.03 (2)	47.10 (3)
				KFM	1.51 (2)	1.35 (3)	0.16 (1)	45.10 (2)
				TWK	2.42 (3)	0.37 (2)	2.04 (3)	47.87 (4)
				RDM	7.72 (4)	4.45 (4)	3.27 (4)	45.01 (1)

As indicated in Table 9, the interaction between the releasing rules and the dispatching rules had significant effects on all performance measures. Hence, it is necessary to seek the best combinations of scheduling rules under the various performance measures. The best combination of scheduling rules is found by using Duncan's multiple range test for the four performance measures as shown in Table 11. Two results can be seen from Table 11. First, no combination of scheduling rules can satisfy all performance measures. For the MAMD performance measure, the POISSON/COVERT combination performed the best. For the MT performance measure, the WR/COVERT combination performed the best. For the ME performance measure, the combination of SA/COVERT performed the best. For the MAFT performance measure, the SA/EDD combination performed the best. For the MAMD, MT and ME performance measures, the combinations with CR, COVERT rules were superior to the others. This is consistent with the result in Table 9, which shows that larger performance measure improvements come from the dispatching rule rather than from the releasing rule.

5. CONCLUSIONS

In a wafer fabrication factory, the completion time for an order can be affected by many factors related to the order characteristics, shop condition and pre shop pool condition. The level of influence of each factor on the completion times for the orders depends on the releasing and dispatching rules used.

In practice, when the capacity of a wafer fabrication factory is fully loaded, the manager usually uses the TWK rule to assign the due date for an order. Using the TWK rule causes a poor due date performance. So as to provide a precise due date for customers, this paper used actual data from a wafer factory to construct two due date assignment models. A method was used to identify the factors that had significant effects on the order queue times. SFM based on the significant factors and KFM based on the most significant factor were constructed for improving the due date performance.

Statistical analysis of the simulation results indicated that the SFM and KFM rules perform better than the TWK and RDM rules. The SFM and KFM rules are recommended as the due date assignment rules in a wafer factory to reduce the cost of changing the order due date.

No significant difference was found between the SFM and KFM in all performance measures. Because the number of factors used in the SFM rule is greater than those used in the KFM rule, the cost of exercising the SFM rule is greater than exercising the KFM rule. Therefore, the KFM rule is recommended as the due date assignment rule in a wafer factory.

Releasing, dispatching and due date assignment rules have significant effects on all performance measures. When the capacity of the wafer factory is fully loaded, the simulation test results showed that the scheduling rule had a significant impact on the performance, with greater improvements coming from the dispatching rules than from the releasing rules. In order to improve the due date performance, using combined dispatching rules (CR, COVERT) is recommended.

Table 9. F-value for three-factor analysis of variance for the four performance measures

Factors	MAMD	MT	ME	MAFT
A (releasing rule)	16.09**	15.34**	19.62**	23.71**
B (dispatching rule)	219.19**	32.09**	266.70**	56.04**
C (due de assignment rule)	322.73**	101.98**	123.78**	80.44**
AB Interaction	7.64**	2.42**	13.14**	25.93**
AC Interaction	0.61	0.81	4.30**	9.89**
BC Interaction	4.17**	3.55**	4.77**	12.12**
ABC Interaction	0.67	1.02	2.82**	12.99**

** Significant beyond 0.01

Table 10. Duncan's multiple range test for the MAMD performancemeasure for due date assignment rules (α=0.05)

Releasing	Dispatching				
WR	FIFO	KFM	SFM	TWK	RDM
	EDD	KFM	SFM	TWK	RDM
	CR	SFM	KFM	TWK	RDM
	NexQL	SFM	KFM	TWK	RDM
	SRPT	KFM	SFM	TWK	RDM
	COVERT	SFM	KFM	TWK	RDM
CONWIP	FIFO	KFM	SFM	TWK	RDM
	EDD	SFM	KFM	TWK	RDM
	CR	SFM	KFM	TWK	RDM
	NexQL	SFM	KFM	TWK	RDM
	SRPT	SFM	KFM	TWK	RDM
	COVERT	SFM	KFM	TWK	RDM
SA	FIFO	KFM	SFM	TWK	RDM
	EDD	KFM	SFM	TWK	RDM
	CR	SFM	KFM	TWK	RDM
	NexQL	KFM	SFM	TWK	RDM
	SRPT	SFM	TWK	KFM	RDM
	COVERT	SFM	TWK	KEM	RDM
	SA	SFM	KFM	TWK	RDM
UNIF	FIFO	SFM	KFM	TWK	RDM
	EDD	SFM	KFM	TWK	RDM
	CR	SFM	KFM	TWK	RDM

Table 10. Duncan's multiple range test for the MAMD performancemeasure for due date assignment rules (α=0.05)(cont.)

Releasing	Dispatching				
	NexQL	SFM	KFM	TWK	RDM
	SRPT	SFM	KFM	TWK	RDM
	COVERT	SFM	KFM	TWK	RDM
POISSON	FIFO	SFM	KFM	TWK	RDM
	EDD	SFM	KFM	TWK	RDM
	CR	SFM	KFM	TWK	RDM
	NexQL	SFM	KFM	TWK	RDM
	SRPT	KFM	SFM	RDM	RDM
	COVERT	SFM	KFM	TWK	RDM
TB	FIFO	SFM	KFM	TWK	RDM
	EDD	SFM	KFM	TWK	RDM
	CR	SFM	KFM	TWK	RDM
	NexQL	SFM	KFM	TWK	RDM
	SRPT	SFM	KFM	TWK	RDM
	COVERT	SFM	KFM	TWK	RDM
	TB	SFM	KFM	TWK	RDM
VCEDD	FIFO	SFM	KFM	TWK	RDM
	EDD	SFM	KFM	TWK	RDM
	CR	SFM	KFM	TWK	RDM
	NexQL	SFM	KFM	TWK	RDM
	SRPT	SFM	KFM	TWK	RDM
	COVERT	SFM	KFM	TWK	RDM

Table 11. The best combinations of scheduling rules of Duncan's test

Combination of scheduling rule	MAMD	Combination of scheduling rule	MT	Combination of scheduling rule	ME	Combination of scheduling rule	MAFT
5,6	2.86	1,6	1.06	3,6	1.06	3,2	41.89
4,6	3.19	4,3	1.13	3,3	1.12	4,2	42.28
7,6	3.21	4,6	1.37	2,6	1.15	2,5	42.70
4,3	3.24	2,3	1.47	5,6	1.21	6,4	43.44
1,3	3.29	1,3	1.50	4,1	1.26	4,5	43.81
7,3	3.32	5,3	1.55	2,1	1.37	3,5	44.10
1,6	3.43	7,3	1.58	6,6	1.59		
2,6	3.59	7,6	1.59	7,6	1.62		
5,3	3.65	5,6	1.64	3,2	1.69		
2,3	3.75	6,8	1.72	3,1	1.71		
3,6	4.10	5,2	1.95	1,1	1.71		
3,3	4.11	7,1	2.36	7,3	1.74		
2,1	4.58	2,6	2.44	1,3	1.78		
1,2	4.67	6,3	2.64	1,2	1.78		
4,1	4.84	1,4	2.87	5,1	1.79		

Table 11. The best combinations of scheduling rules of Duncan's test (cont.)

Combination of scheduling rule	MAMD	Combination of scheduling rule	MT	Combination of scheduling rule	ME	Combination of scheduling rule	MAFT
5,1	4.85	3,3	2.99	4,6	1.82		
7,1	4.92	1,2	3.03	5,4	1.86		
1,4	5.04	3,6	3.04	6,2	1.88		
		5,1	3.06	4,2	1.91		
		1,5	3.18	2,4	1.92		
		2,1	3.21	4,4	2.06		
		7,5	3.28	5,3	2.09		
		2,2	3.3	4,3	2.11		
				1,4	2.17		

* the of Duncan's Test is 0.05
** number1,number2: number1 is releasing rule (1:WR, 2:CONWIP, 3:SA, 4:UNIF, 5:POISS, 6:TB, 7:WCEDD); number2 is dispatching rule (1:FIFO, 2:EDD, 3:CR, 4:NexQL, 5:SRPT, 6:COVERT, 7:SA, 8:TB)

APPENDIX A : List of prediction factors

Main class	Subclass	Number of factors included
Shop condition (1)	shop status (1-1)	1. total WIP in the shop 2. total remaining workload in the shop 3. total WIP of DRAM in the shop 4. total WIP of SRAM in the shop 5. total WIP of LOGIC in the shop 6. total remaining workload of DRAM in the shop 7. total remaining workload of SRAM in the shop 8. total remaining workload of LOGIC in the shop
	bottleneck resource status (1-2)	9. number of lots in the bottleneck 10. total remaining workload in the bottleneck 11. total remaining workload of DRAM in the bottleneck 12. total remaining workload of SRAM in the bottleneck 13. total remaining workload of LOGIC in the bottleneck 14. total WIP of DRAM in the bottleneck 15. total WIP of SRAM in the bottleneck 16. total WIP of LOGIC in the bottleneck 17. number of shot-down machine in the bottleneck 18. total remaining workload of the bottleneck in the shop
	constraint resource status (1-3)	19. number of WIP in the IMPLANTER_H 20. number of WIP in the RCA_CLEAN 21. number of WIP in the GATE_OXIDE 22. number of WIP in the LPCVD_POLY 23. number of WIP in the N_DOPE 24. total remaining workload in the IMPLANTER_H total remaining workload in 25. the RCA_CLEAN 26. total remaining workload in the GATE_OXIDE 27. total remaining workload in the LPCVD_POLY 28. total remaining workload in the N_DOPE 29. the WIP of DRAM in the IMPLANTER_H 30. the WIP of SRAM in the IMPLANTER_H 31. the WIP of LOGIC in the IMPLANTER_H 32. the WIP of DRAM in the RCA_CLEAN 33. the WIP of SRAM in the RCA_CLEAN 34. the WIP of LOGIC in the RCA_CLEAN 35. the WIP of DRAM in the GATE_OXIDE 36. the WIP of SRAM in the GATE_OXIDE 37. the WIP of LOGIC in the GATE_OXIDE 38. the WIP of DRAM in the LPCVD_POLY 39. the WIP SRAM in the LPCVD_POLY 40. the WIP LOGIC in the LPCVD_POLY

APPENDIX A：List of prediction factors (cont.)

Main class	Subclass	Number of factors included
Shop condition (1)	constraint resource status (1-3)	41. the WIP of DRAM in the N_DOPE 42. the WIP of SRAM in the N_DOPE 43. the WIP of LOGIC in the N_DOPE 44. total remaining workload of DRAM in the IMPLANTER_H 45. total remaining workload of SRAM in the IMPLANTER_H 46. total remaining workload of LOGIC in the IMPLANTER_H 47. total remaining workload of DRAM in the RCA_CLEAN 48. total remaining workload of SRAM in the RCA_CLEAN 49. total remaining workload of LOGIC in the RCA_CLEAN 50. total remaining workload of DRAM in the GATE_OXIDE 51. total remaining workload of SRAM in the GATE_OXIDE 52. total remaining workload of LOGIC in the GATE_OXIDE 53. total remaining workload of DRAM in the LPCVD_POLY 54. total remaining workload of SRAM in the LPCVD_POLY 55. total remaining workload of LOGIC in the LPCVD_POLY 56. total remaining workload of DRAM in the N_DOPE 57. total remaining workload of SRAM in the N_DOPE 58. total remaining workload of LOGIC in the N_DOPE 59. number of shot-down machine in the N_DOPE 60. number of shot-down machine in the IMPLANTER_H 61. number of shot-down machine in the RCA_CLEAN 62. number of shot-down machine in the GATE_OXIDE 63. number of shot-down machine in the LPCVD_POLY 64. total remaining workload of IMPLANTER_H in the shop 65. total remaining workload of RCA_CLEAN in the shop 66. total remaining workload of GATE_OXIDE in the shop 67. total remaining workload of LPCVD_POLY in the shop 68. total remaining workload of N_DOPE in the shop
	recently completed orders (1-4)	69. average flow time of three lots which had only just finished 70. average flow time (three lots) of SRAM, which had only just finished. 71. average flow time (three lots) of DRAM, which had only just finished. 72. average flow time (three lots) of LOGIC, which had only just finished. 73. average waiting time (three lots) in the shop which had only just finished 74. average waiting time (three lots) of DRAM in the shop which had only just finished 75. average waiting time (three lots) of SRAM in the shop which had only just finished 76. average waiting time (three lots) of LOGIC in the shop which had only just finished
Order characteristics (2)		77. total workload of the order 78. total workload on the bottleneck of the order 79. total workload on the IMPLANTER_H of the order 80. total workload on the RCA_CLEAN of the order 81. total workload on the GATE_OXIDE of the order 82. total workload on the LPCVD_POLY of the order 83. total workload on the N_DOPE of the order 84. product type of the order (1.DRAM, 2.SRAM 3.LOGIC)
Pre shop pool condition (3)	pre shop pool status (3-1)	85. number of lots in the pre-shop-pool 86. number of lots of DRAM in the pre-shop-pool 87. number of lots of SRAM in the pre-shop-poop 88. number of lots of LOGIC in the pre-shop-poop
	recently completed orders (3-2)	89. average waiting time (three lots) in the pre-shop-pool which had only just finished 90. average waiting time (three lots) of DRAM in the pre-shop-pool which had only just finished 91. average waiting time (three lots) of SRAM in the pre-shop-pool which had only just finished 92. average waiting time (three lots) of LOGIC in the pre-shop-pool which had only just finished

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